June 1953

NUCLEONICS

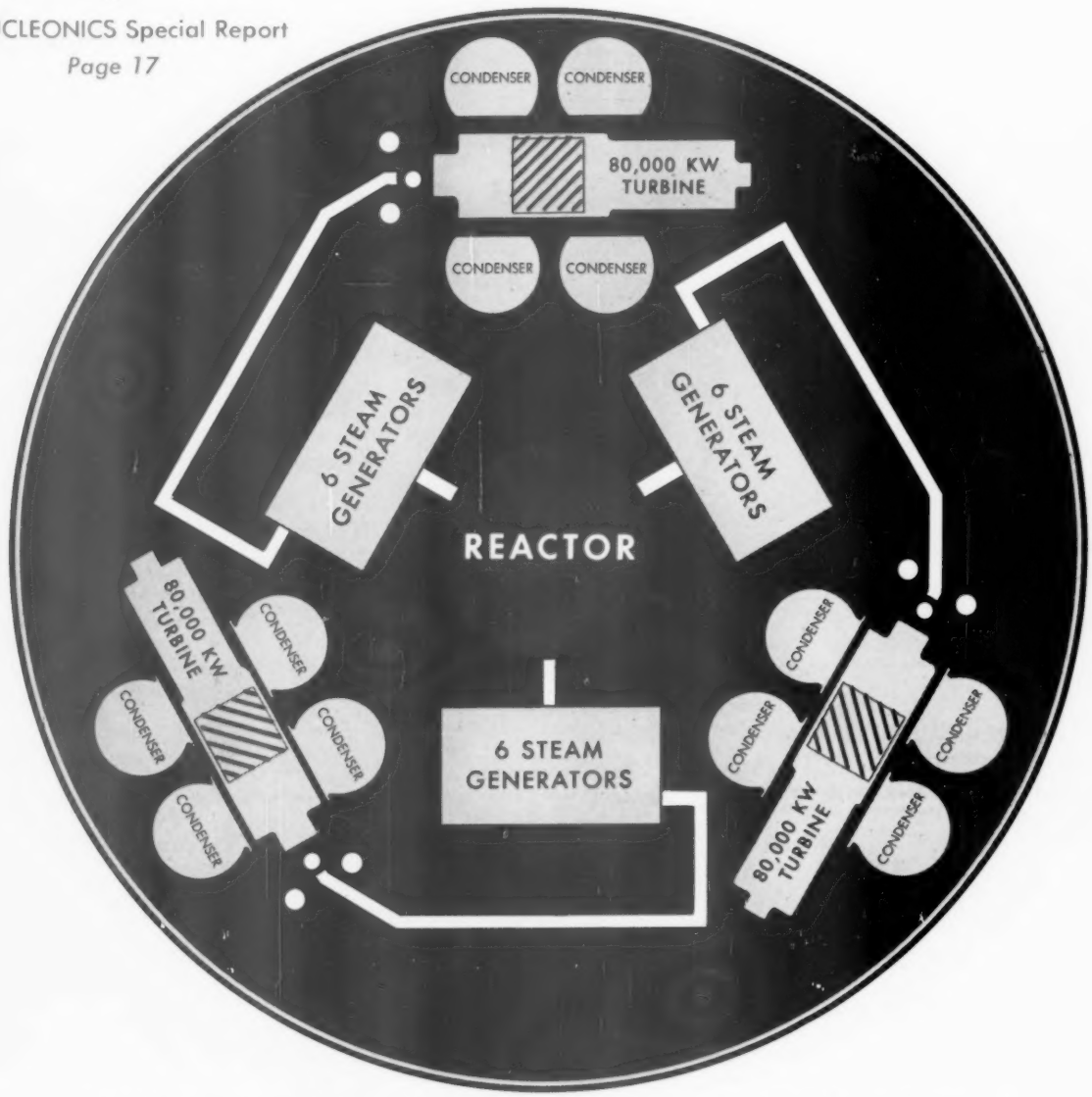
A McGRAW-HILL PUBLICATION ★ TWO DOLLARS

Materials and Equipment for Reactors

•

A NUCLEONICS Special Report

Page 17



To minimize piping length, turbines in this 225-Mw reactor power plant are arranged in circle around reactor. This heavy-water-cooled thermal reactor is one of designs proposed in feasibility studies described on p. 49

Here's a CVC team that meets every *high vacuum* leak detection requirement

Consolidated Engineering Leak Detector, Model 24-101A *(above) is a simplified mass spectrometer sensitive to minute traces of helium. It can be used with either the probe or envelope method. The self-contained unit includes mechanical and diffusion pump, and all necessary controls and instruments.*

CVC Leak Detector, Model LD-01 *(above right) uses a sensitive element containing a heated platinum anode and cold cathode with relatively low voltage between them. The circuit uses standard radio tubes, operates on 115-volt ac current.*

For routine maintenance of your high vacuum system—*CVC's* Model LD-01 Leak Detector is a compact, easily portable unit. It's simple to operate. You just connect the sensitive element to your vacuum system and pump a moderate vacuum. Then, direct a small jet of harmless Freon Gas at suspected spots and watch the meter. You get a direct indication of leak rate.

For production work—the Consolidated Engineering Leak Detector (Model 24-101A) will solve your problems. Whether it's a *large vacuum metallizer, vacuum furnace, refrigerator compressor drying system* or *TV-tube pumping system*, this versatile and extra sensitive unit will tell you when it's absolutely leak tight. Most specifications for hermetically sealed relays now require a leak tolerance detectable *only* with this type of unit.

Operation is simple—just play helium on the suspected area. An audio system tells the size of the leak by a low or high-pitched sound, or you can watch for it on a meter.

Either or both of these instruments will save you many hours of wearisome searching for vacuum leaks. For information on this or any other equipment, for the creation, measurement or use of *high vacuum*, write to ***Consolidated Vacuum Corporation, Rochester 3, New York*** (A subsidiary of Consolidated Engineering Corporation, Pasadena, Calif.) Sales offices: Menlo Park, Calif. • Chicago, Ill. Camden, N. J. • New York, N. Y.

CVC

formerly DPi Vacuum Equipment Dept.

Consolidated Vacuum Corporation

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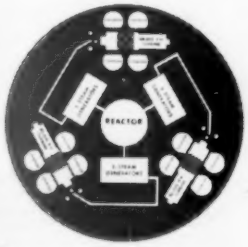
high vacuum research and engineering

NUCLEONICS

JUNE • 1953

Vol. 11, No. 6



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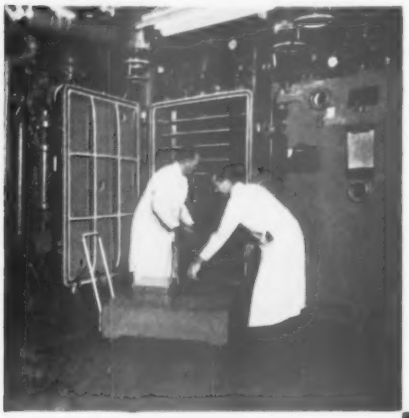
Stokes equipment is used for the shelf-drying of procaine penicillin under vacuum at the New Brunswick, N. J. plant of E. R. Squibb & Sons.



One of the uses for the complete custom-built installation of Stokes vacuum freeze-drying equipment in Pitman-Moore Company's new million-dollar plant at Indianapolis, Ind. is to produce gamma globulin to combat poliomyelitis. One of the steps is drying the material from its frozen state. Operators are shown removing trays of gamma globulin from Stokes freeze-dryers at temperatures of 40° below zero F.

Diesel locomotive armature being removed, after impregnation, from Stokes high vacuum impregnating tank in the San Bernardino, Calif., plant of Atchison, Topeka & Santa Fe Railway. Electric motors for the Santa Fe's "Chief" and "Super Chief" develop such excessive heat that ordinary insulation would swell or burst, causing the rotors to "freeze" in the mounting. By impregnating these rotors with protective resins under high vacuum in Stokes impregnators, each turn of wire is held rigidly in place and the motors operate without interruption.

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The first commercial production of blood plasma to save human lives was initiated by Stokes engineers on Stokes vacuum processing equipment. Hog cholera serum to protect and increase the world's meat supply is largely produced on Stokes equipment by vacuum processing methods. More recently, Stokes freeze-drying equipment has been used to produce gamma globulin, the first real ray of hope in the fight against paralytic poliomyelitis.

New markets for low-cost metals and plastics which simulate more costly pieces have been created through the use of Stokes vacuum metallizing equipment. Electric and electronic equipment is now processed in Stokes vacuum impregnation units to prepare it for the heavy loads and exacting requirements of modern electric and electronic practice.

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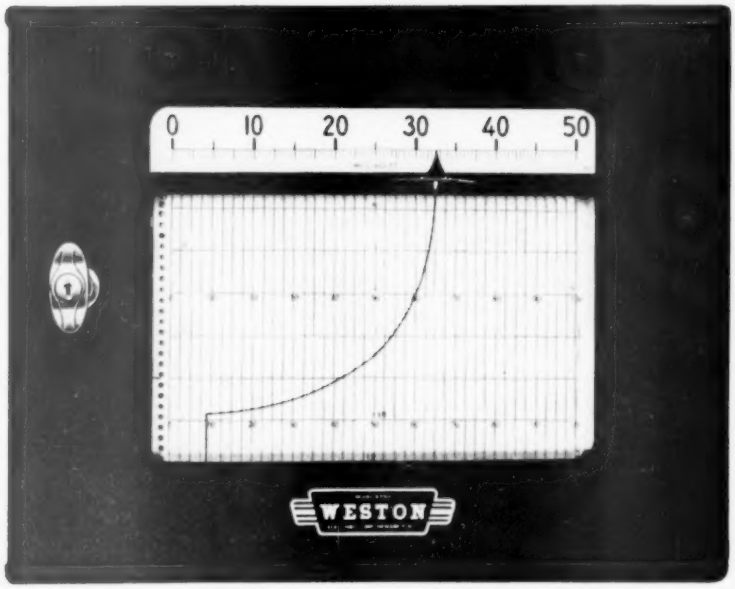

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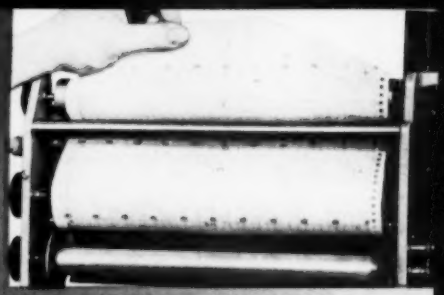
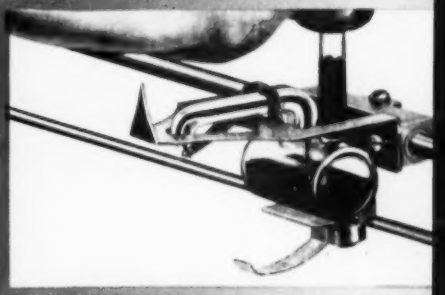
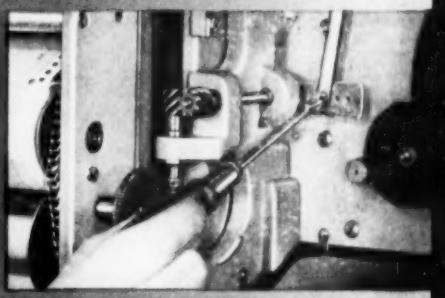
INDICATE — RECORD — CONTROL



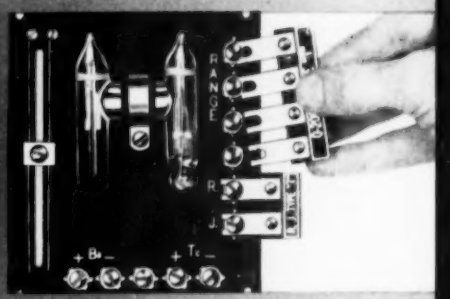
TO CHANGE CHARTS, you simply swing chart frame open a full 180°, insert chart and swing it over timing drum and across front of frame and fasten. No loose pieces to handle!



TO REFILL PEN, simply open chart frame completely exposing pen for quick, easy filling. Recorder continues operation and charts remain in time sequence during filling.

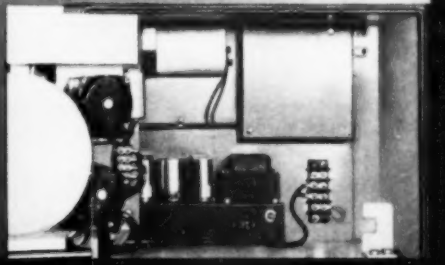


TO CHANGE CHART SPEEDS, a simple screwdriver adjustment gives you a choice of 5 different speeds. These speeds are doubled or quadrupled by changing one worm and gear assembly.



TO CHANGE RANGES, you simply substitute the desired range standard. The reference junction compensation is changed in like manner. No soldered connections to break!

TO REMOVE THE AMPLIFIER, you simply take out two screws and pull two plugs. With no soldered connections servicing is quick and simple. ▼



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A A background of seven years' experience wholly in the field of commercial radioactivity. In seven years Tracerlab has performed a wide range of research and development projects that will interest you.

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   Development of a wide range of portable and laboratory detection equipment based on ionization chamber, geiger instruments, quartz-fiber and scintillation methods
   Tracer experiments
   Extensive radio-analytical studies
   Health physics programs
   Shielding

2. Conducted research projects totaling approximately $5,000,000 for all branches of the armed services, for the A.E.C. and for private industry.

3. Recently completed a year-long, Tracerlab financed study of the feasibility of private isotope reactor ownership under letter-contract from the A.E.C.

4. Assembled a staff of approximately two-hundred, well-qualified, experienced technical people who are capable of handling projects extending into many fields of radioactivity. Extensive and complete laboratory and production facilities are available at Tracerlab, both in Boston, Massachusetts and Berkeley, California.

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If you require a scintillation counter tube having high efficiency—and a resolving time of only a small fraction of a micro-second—don't overlook the RCA-6199. Current amplification is about 600,000 when the tube is operated from a 1000-volt supply.

For technical data or design help, write RCA Commercial Engineering, Section 62-FR, Harrison, N. J. Or just call your nearest RCA Field Office:

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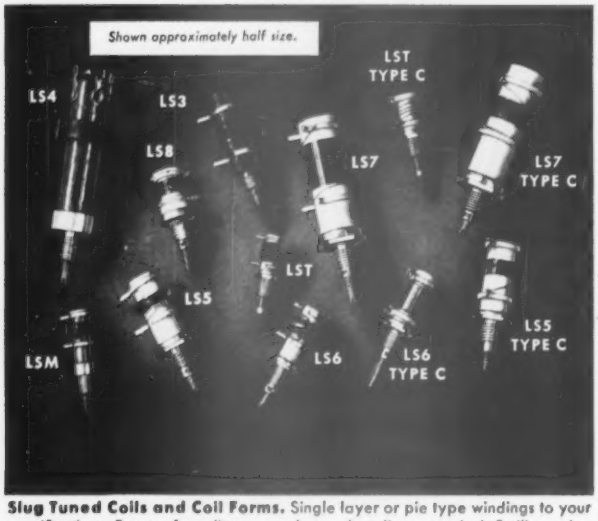
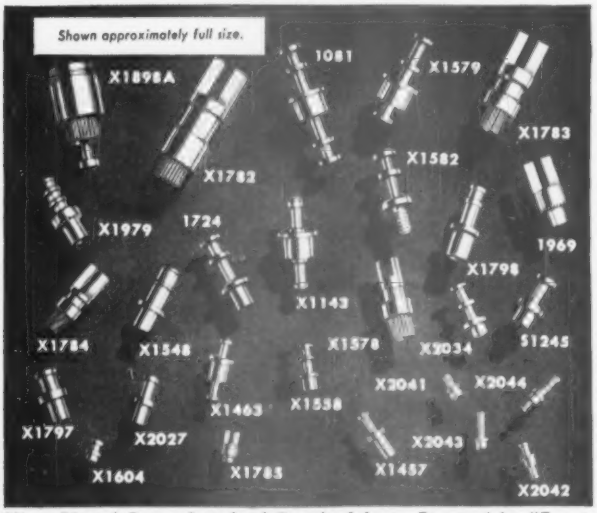


Slug Tuned Coils and Coil Forms. Single layer or pie type windings to your specifications. Forms of quality paper base phenolic or grade L-5 silicone impregnated ceramic. Mounted bushings are cadmium plated brass; ring type terminals are silver plated brass. All units include slugs and mounting hardware. Type C (above) available with retaining collars of silicone fibreglas. Note: Regular, CTC Coil Form Kit is available. Also available, new Coil Kit, Type X2060, with windings on standard LS-6 Forms.



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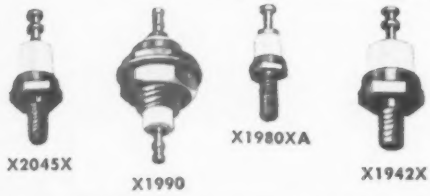
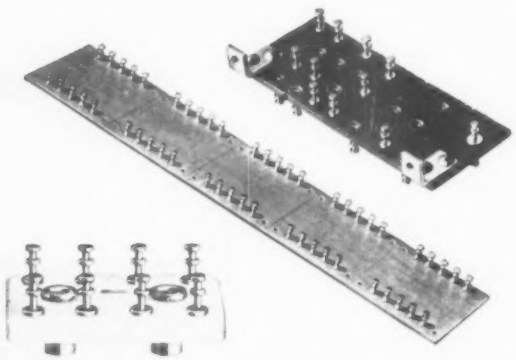


Insulated Terminals. Grade L-5 ceramic, silicone impregnated for maximum performance over broad humidity range. Rivet or screw stud type. 5 lengths of dielectric. Also available: phenolic in rivet or screw-stud mountings; ceramic with internal screw thread.

Hardware. Includes panel screws, thumb screws, dial locks, shaft locks, handles and handle ferrules, tube clamps, terminal board brackets, standoff mounts and spacers.



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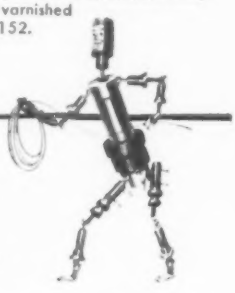

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SPERRY GYROSCOPE COMPANY uses a two-channel Sanborn Recording System for basic research on their Zero Reader* Flight Director, a device which simplifies the manual control of aircraft. The Sanborn System shown above is recording the output of a flight simulator that solves Zero Reader equations.

*T. M. REG. U. S. PAT. OFF.

At McDONNELL AIRCRAFT CORPORATION the movements of a guided missile are simulated by high-precision analog computers which in turn send *eight* different resultant electric signals into two Sanborn four-channel Recording Systems (left) for the graphic recording of the hypothetical results of the guided missile problem.

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CAMBRIDGE 39, MASSACHUSETTS

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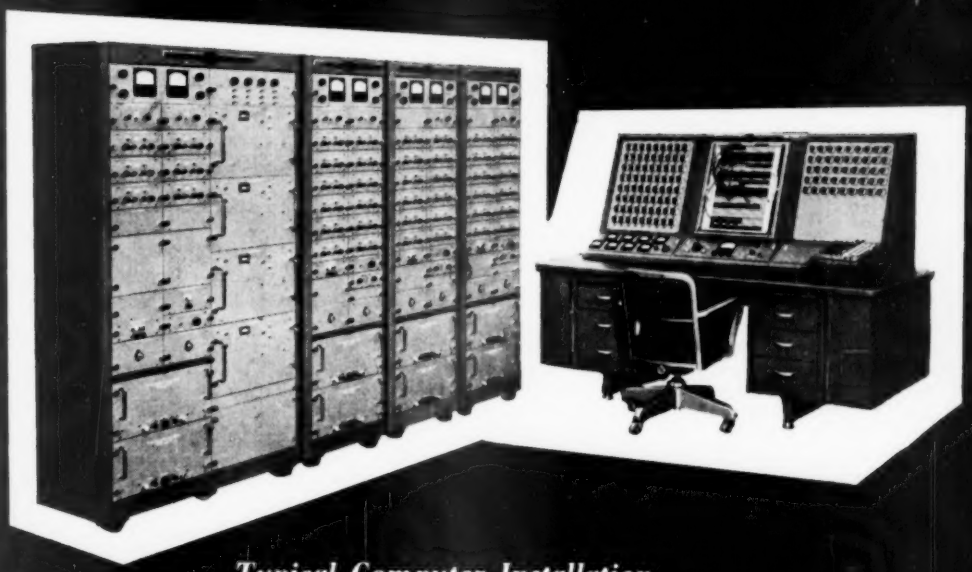

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- A new high quality patch board assembly, using an 1800 position pre-patch panel made of metal to avoid leakages between terminals and to improve overall computer accuracy.
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- Centralized operation of the entire computer from a control console providing maximum ease of operation and flexibility in the use of the system plus minimizing the cost of expansion.

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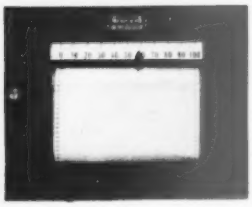
Special ElectroniK recording instruments of interest to research men:



FUNCTION PLOTTER—automatically plots the relationship, $y = f(x)$, between any two variables that can be converted to electrical signals.

TWO-PEN RECORDER: simultaneously records two variables on a single chart . . . both pens can traverse full width of 11-inch chart.

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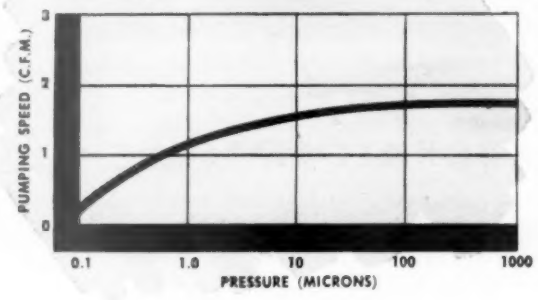

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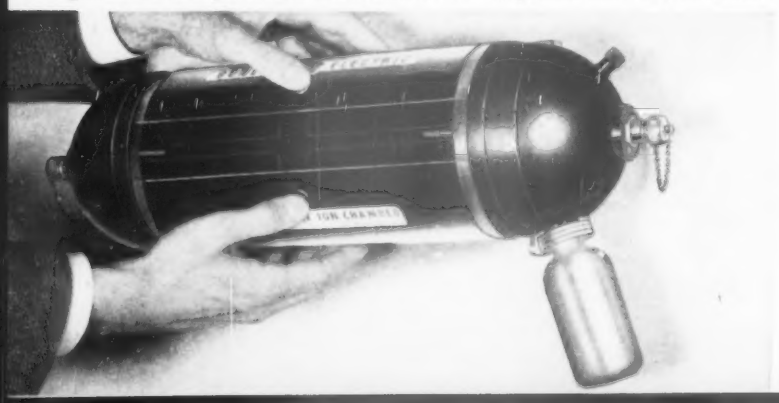

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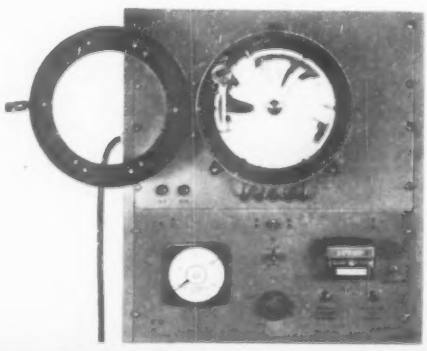


NUCLEONICS JUNE, 1953

Jerome D. Luntz, *Editor*

Policies on Radiation Exposure

BEFORE THE END of this century, uranium and thorium will be vital natural resources in our peacetime economy. Many more people than are now concerned with atomic energy will be involved—whether they be research workers using radioisotopes or operators of power reactors.

It is of tremendous significance to these workers and to the race as a whole that an accurate and realistic attitude be taken toward the setting of official policies on maximum permissible exposure (MPE) levels. In learning to live with radiation, people must not only be secure in the knowledge that they are not being harmfully exposed to radiation but also that they are not being required to set up unnecessarily inconvenient and expensive protective measures.

VARIOUS BODIES—national and international—are considering this problem. The National (U. S.) Committee on Radiation Protection has two subcommittees concerned with permissible dose, one from external, the other from internal sources. The Tripartite (U. S., U. K., Canada) Committee on Radiation Tolerances has met on a number of occasions, most recently in April at Harriman, New York. The International Commission on Radiological Protection will meet again next month in Copenhagen.

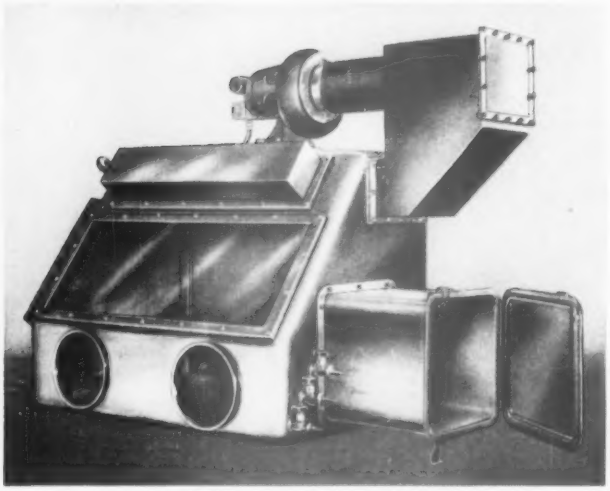
All of these groups are made up of outstanding authorities. But experts can only be as good as the knowledge they have. And the fact is that data on the biological effects of radiation on man are sparse. Although great strides have been made as a result of the mammoth atomic energy effort of the past ten years, a good part of our present thinking is based on work done prior to the war.

Factors of safety have always been employed in the past ten years in the establishment of MPE values. Even then, most large laboratories have added their own safety factor. In the recently issued report of the subcommittee on internal dose, the subcommittee suggests that, because of the uncertainties involved in their determinations, a factor of ten should be used.

SOME OF THE PROBLEMS faced by the subcommittee on external dose are quite basic and controversial. Geneticists feel that the average exposure per person in the total population is much more important than the absolute exposure to any one person. Nevertheless, this must be low enough to prevent other injuries to the person in his lifetime. According to the genetic view the lifetime dose received by those occupationally exposed to radiation may be quite high, provided their number constitutes a small fraction of the total population. However, as more and more persons are exposed, the permissible lifetime dose for those occupationally exposed becomes lower. The geneticists are concerned about harmful mutations which would become evident in the course of all subsequent generations. They point out that any addition to the number of undesirable genes already present in man should be avoided. Therefore, they recommend that the average accumulated dose for the whole population of reproductive age be of the order of five roentgens. Genetic damage to the race is not the controlling factor at this time, because of the relatively small number of people occupationally exposed, but its importance is bound to increase with time in the atomic age. At some future time the matter may become one of national policy at a high level in which the possible harm to the race will be weighed against the benefits to be derived from the wider applications of atomic energy. The MPE values recommended by the National Committee on Radiation Protection are intended to prevent injury to the individual in his lifetime.

It is obviously quite impossible at this time to establish with any certainty MPE values that will be "good" ten or twenty years from now. A conservative and consequently safe attitude has been taken thus far. It is hoped that experience will prove it possible to adopt more liberal standards so as to facilitate the broadest and most economic application of atomic energy. At any rate, it is obvious that avoidance of unnecessary exposure will make it possible to do more work involving unavoidable exposure to radiation.

STAINLESS STEEL EQUIPMENT
FOR RESEARCH WITH RADIOACTIVE MATERIALS



Above: **LOW INTENSITY DRY BOX** — Designed for the safe handling of radioactive materials. Also useful for work with bacteria, viruses and other hazardous substances. Other types of enclosures available include vacuum dry boxes, biological safety cabinets and research enclosures, and a complete interchangeable dry box system.

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Selection of

Materials and Equipment for Reactors

1. **MATERIALS** ..... p. 18
   Structural, moderator, reflector, shielding
2. **COOLANTS** ..... p. 27
   Liquids, liquid metals, gases; components and systems
3. **REACTOR OPERATION** ..... p. 35
   Instruments, accessories, control materials, driving mechanisms
4. **REACTOR RADIATION SAFETY** ..... p. 41
   Protection procedures, systems, instruments, equipment
5. **REACTOR USE FOR RESEARCH** ..... p. 46
   Design criteria, facilities, equipment

Arranged specifically for use by engineers and scientists engaged in reactor work, this report is a compilation of information vital to design, construction, and use of a nuclear reactor. It is a collation of the pertinent unclassified information that has been evolved in many engineering and scientific disciplines.

Information is presented in handbook fashion for easy use. To emphasize the application of this information, it has been arranged according to the phase of reactor technology on which it has the most bearing.

Security restrictions have limited the amount of quantitative data that can be reported in some sections of this report. But enough numerical data have been included to make this report a logical starting place for a consideration of reactor materials and components.

A NUCLEONICS Special Report

STEEL-PLATED CONCRETE BLOCKS shield top of Brookhaven reactor, can be removed for servicing core

Materials

By GEORGE E. EVANS

Oak Ridge National Laboratory
Oak Ridge, Tennessee

PHYSICAL STRUCTURE and operating conditions of a nuclear reactor can vary over extremely wide limits. In principle a reactor may operate at the temperature of liquid air or at white heat; the power level can be milliwatts or megawatts; the pressure can be sub-atmospheric or thousands of pounds per square inch; the size may be smaller than a football or larger than a house.

The selection of a particular set of such physical parameters for a proposed reactor depends ultimately upon its purpose. For instance, a reactor designed to produce mobile power obviously will be a small, high-power-density reactor operating at a sufficiently high temperature to allow efficient conversion of heat into work. Once the purpose of the reactor has been clearly defined—and *only* when the purpose of the reactor has been clearly defined—can one attempt the simultaneous solution of three problems:

1. What is the basic conceptual design of the reactor and its auxiliary facilities (i.e., should the reactor be thermal, intermediate, or fast; heterogeneous or homogeneous; how is the coolant to be circulated; etc).

2. What will be the physical parameters of the reactor under operating conditions (i.e., temperature, pressures, dimensions, masses, etc).

3. What materials will be used, and how can they be obtained, fabricated, joined, etc, to construct the actual reactor and its auxiliaries.

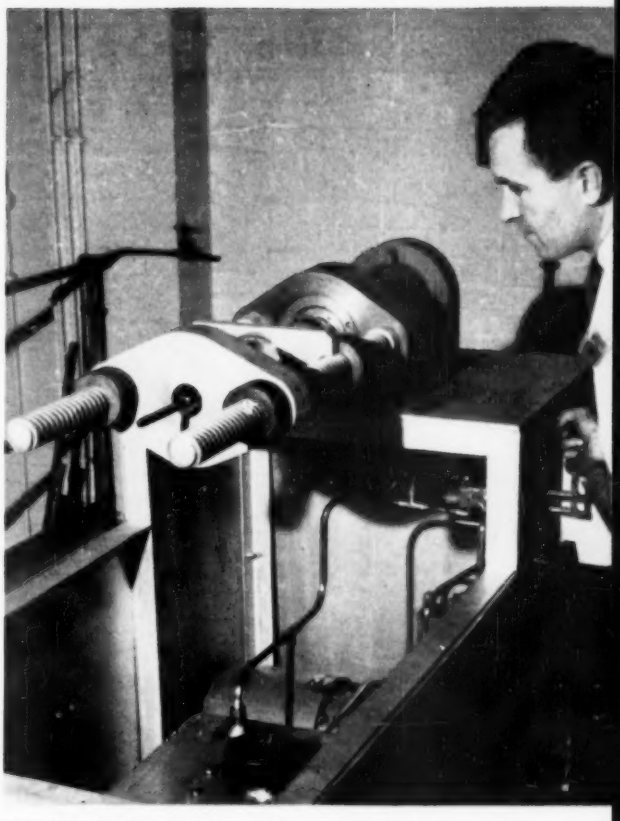
It must be emphasized that these three problems cannot be isolated or studied independently. The selection of a

TABLE 1—Properties of Reactor Materials

Element	*Symbol*	*Atomic no.*	*Atomic wt.*	*Density (gm cm³)*	*Cost ($/lb)**	*Melting point (°C)*
Aluminum	Al	13	26.98	2.70	0.30–0.60	660.2
Beryllium	Be	4	9.013	1.85	(175)	1,300
Magnesium	Mg	12	24.32	1.74	0.25	651
Molybdenum	Mo	42	95.95	10.2	3.00	2,620
Nickel	Ni	28	58.69	8.9	0.60	1,455
Tantalum	Ta	73	180.88	16.6	65	2,996
Titanium	Ti	22	47.90	4.5	(15)	1,725
Vanadium	V	23	50.95	6.02	?	1,735
Tungsten	W	74	183.92	19.3	6.00	3,410
Zirconium	Zr	40	91.22	6.5	20–125	1,830
18-8 Stainless steel (Fe, Cr, Ni, Mn, Nb)				7.92	(0.60)	1,399–1,421
Inconel "X" (Ni, Cr, Fe, Ti, Nb)				8.3	(3.00)	1,395–1,425

* Cost figures in parentheses are estimated. † The following ab-

ZIRCONIUM is a key metal in reactor construction. Pure metal shown was produced by crystal bar process by Westinghouse



GRAPHITE ROD is extruded at Harwell, England, from coke-pitch mixture. Baking at high temperature produces pure graphite

Specific heat (cal/gm/°C)	*Thermal expansion coefficient (per °C × 10⁶)*	*Thermal conductivity (cal/cm²/sec/°C/cm)*	*Resistivity (μohm-cm)*	*Modulus of elasticity (10⁶ psi)*	*Poisson's ratio*	*Hardness (BHN)*	*Tensile strength (10³ psi)*		*Elongation in 2 in. (%)*		*Crystal structure†*	*α-β phase transition*	*β phase structure*	*σ_a, neutron (barns)*
							Annealed	*Cold worked*	*Annealed*	*Hardened*				
0.22	24	0.54	2.65	10	0.3	20–25	13	24	35	5	FCC			0.22
0.5	12	0.3	4.0	42		110	45		1–2		HCP			0.010
0.25		0.35		6.5	0.35	50	32–46	32–50	16–12	8–3	HCP			0.059
0.065	5.5	0.346	4.8–5.7	40–50	0.31	147	100	250	10–20	2–5	BCC			2.4
0.11	13	0.14	6.1–10	30		75	47	125	15	3	FCC			4.5
0.036	6.5	0.130	12.5	27		75–125	50	125	40	1	BCC			21
0.129	8.5	(low)	48–90	16.8		200	80	122	24	7.5	HCP	880	BCC	5.8
0.12			26	20–22	0.36	260‡					BCC			4.8
0.034	4.0	0.476	5.5	50–60		260	50	300			BCC			19
	4.96–5.8	0.05	41	12	0.33		35	85	31	18	HCP	863	BCC	0.18
0.12	16.7	0.039	71	29	0.38	160	90		45		FCC			2.9
0.11	13.9	0.035	122	31	0.29	200–400	160–180		24		FCC			4.1

breviations are used: FCC, face-centered cubic; BCC, body-centered cubic; HCP, hexagonal close packed. ‡ Cold worked.

TABLE 2—Nuclear Properties of Structural Materials

Element	*Symbol*	*Atomic number*	*Natural element σ_a (barns)*	*Isotope*	*Abundance in natural element (%)*	*Activation cross section (barns)*	*Hardest gamma rays (Mev)*	*Half-life*
Beryllium†	Be	4	0.01					
Boron‡	B	5	750					
Carbon†	C	6	0.0045					
Magnesium†	Mg	12	0.059	26	11.1	0.05	1.0 . . .	9.6 m
Aluminum†	Al	13	0.22	27	100	0.22	1.78	2.3 m
Titanium†	Ti	22	5.8	50	5.3	0.14	0.32	6 m
Vanadium*†	V	23	4.7	51	99.8		1.46	2.6 m
Chromium†	Cr	24	2.9	50	4.4	16	0.32	27 d
Manganese*†	Mn	25	12.6	55	100	12.6	3.0	2.6 h
Iron†	Fe	26	2.4	58	0.33	0.8	1.3 . . .	45 d
Cobalt*	Co	27	34	59	100	14	1.33	11 m
				59	100	20	1.33	5.2 y
Nickel†	Ni	28	4.5	64	1	3.0	1.5 . . .	2.56 h
Copper†	Cu	29	3.6	63	69	4.3	1.34 . . .	12.8 h
				65	31	2.1	1.04	5.17 m
Zinc*†	Zn	30	1.06	64	48.9	0.5	1.12	250 d
Zirconium†	Zr	40	0.18	94	17.4	0.07	0.92	65 d
Niobium†	Nb	41	1.1	93	100	1	0.9	6.6 m
Molybdenum†	Mo	42	2.4	98	23.8	0.13	0.73	67 h
				100	9.5	0.2	0.96	15 m
Silver*	Ag	47	60	107	51.4	30	0.61	2.3 m
				109	48.6	82	0.9	24 sec
				109	48.6	2	0.66	270 d
Cadmium‡	Cd	48	3,100	106	1.2	1	0.85	6.7 h
				114	28.8	0.14	1.28	43 d
				114	28.8	1.1	0.52	54 h
				116	7.6	1.4	1.2	2.9 h
Indium*‡	In	49	190	115	95.8	145	2.1 . . .	54.3 m
Tin†	Sn	50	0.6	124	6.0	0.2	1.4 . . .	9.5 m
Antimony*	Sb	51	5.3	121	57.2	5.7	0.69 . . .	2.8 d
Lanthanum*	La	57	8.8	139	99.9	8.8	2.5 . . .	40 h
Praseodymium*	Pr	59	11	141	100	11	1.8 . . .	19.3 h
Samarium	Sm	62	10,000					
Europium*‡	Eu	63	4,300	151	47.8	1,400	0.94 . . .	9.3 h
				151	47.8	7,000	1 . . .	13 y
				153	52.2	400	1.3 . . .	16 y
Gadolinium‡	Gd	64	36,000					
Hafnium‡	Hf	72	120	174	0.18	~500	0.34 . . .	70 d
				180	35.3	13	0.61	45 d
Tantalum*†	Ta	73	21	181	100	21	1.2 . . .	111 d
Tungsten*†	W	74	19	186	28.7	34	0.7 . . .	24 h
Rhenium*	Re	75	84	185	37.1	100	0.76 . . .	91 h
				187	62.9	63	2.4 . . .	17 h
Iridium*	Ir	77	440	191	38.5	700	0.6 . . .	75 d
				193	61.5	120	>2.2 . . .	19 h
Gold*	Au	79	95	197	100	95	1.1	2.7 d
Mercury‡	Hg	80	360					

* Major contributors to persistent induced activity even if present in relatively small quantities. Elements possessing isotopes which combine high activation cross section, high isotopic abundance, intermediate half-life and relatively hard gamma rays.

† Major or common minor components of structural metals and alloys associated with reactor technology.

‡ Elements whose high neutron absorption cross section makes them particularly undesirable as an impurity (especially in moderators).

conceptual design employing thin-walled heat-exchanger tubes, for example, will place immediate restrictions upon the selection of materials capable of fabrication to form such tubes; and the selection of a material of suitable fabricability immediately influences the physical parameters by placing limits on the temperature, allowable stresses, etc. In the following discussion, no further attempt will be made to distinguish between the selection of a conceptual design, the selection of physical parameters of the reactor system, and the selection of materials, since ultimately these three problems must be treated as one problem: to design an optimum reactor to fulfill some specified purpose.

It is simpler to discuss the factors involved in the selection of reactor materials if we classify various materials with respect to their function in the reactor. One classification is:

1. Fuels and fertile materials. These must contain the fissionable isotope (e.g. U^{235}, U^{233}, Pu^{239}) required to sustain the chain reaction; or contain fertile isotopes (e.g. Th^{232}, U^{238}) which upon neutron capture lead to the production of new fuel.

2. Moderators and reflectors. These must contain isotopes of small atomic mass, low neutron capture, and high neutron-scattering cross section so as to reduce neutron energy efficiently. A reflector may surround the active core of the reactor to scatter back into the core some of the neutrons which otherwise would be lost by leakage into the shield. It may or may not be an extension of the moderator.

3. Coolants. These must remove fission heat from the reactor.

4. Structural materials. These must supply the necessary mechanical framework of the reactor, including such components as pressure shells, tanks for liquid moderators, ducts for coolant flow, and positioning supports for fuel rods.

5. Shielding materials. These must confine dangerous radiations within the reactor.

These categories are not mutually exclusive; a liquid moderator such as water may also serve as coolant; a solid moderator such as graphite may also serve as a structural material; the fuel and moderator may be combined in a single component; etc. In addition there are a variety of materials not included in the preceding categories, such as control materials, instrument components, and experimental equipment.

In view of existing security regulations, this article will not attempt a discussion of the factors involved in the design and fabrication of nuclear fuel elements. The subject of coolants is treated separately in the following article. The remainder of this article will discuss the factors relevant to a selection of structural, moderator, reflector, and shielding materials.

STRUCTURAL MATERIALS

Some of the more important physical and mechanical properties of potential reactor materials are compared in Table 1. For structural materials the significance of mechanical properties such as ductility, strength, and hardness is obvious. Since a reactor is a heat-producing device, thermal properties such as thermal conductivity, coefficient of expansion, melting point, high-temperature strength, and phase transitions are of importance, particularly at high power densities.

Material costs are of considerable importance, especially since the range of prices of competing materials is so broad. For those new metals which have been produced only in pilot-plant quantities or which have not been offered for sale on a competitive market, no "price" can be clearly defined. In such cases the "price" listed in Table 1 is an order-of-magnitude estimate by the author of the costs chargeable per pound of metal in a form and purity suitable for reactor application and is included only to allow comparison of orders of magnitude. Speaking more generally, the cost of any reactor material can be evaluated only by determining the total cost of an entire reactor plant incorporating the use of the given material, including the initial materials costs, fuel inventory charges, costs of fuel reprocessing, design and construction costs, costs of auxiliary facilities (pumps, pressurizing systems, power generation equipment, fuel handling equipment), control and instrumentation costs, maintenance, operating and overhead costs.

The problems encountered in selecting structural materials for a reactor are similar to those found in selecting materials for a heat exchanger operating at the same temperature, pressure, and heat transfer rate, except that in the reactor system the nuclear properties of the materials are also of vital importance. Some of the pertinent nuclear properties of these materials are listed in Table 2. For application in thermal reactors a low thermal-neutron absorption cross section is important in maintaining a good neutron economy. In intermediate or fast reactors the thermal-neutron absorption is of less significance. In any type of reactor compromises will have to be made between conflicting desiderata of minimum fuel inventory, maximum breeding gain, optimum mechanical and thermal properties, minimum corrosion, and minimum cost.

Also included in Table 2 are values of the activation cross sections, and energies and half-lives of the gamma-rays produced as a result of neutron capture in the structural materials. To simplify repairs or maintenance (if this should become necessary) the gamma rays produced should be either few in number, low in energy, or short in half-life. For materials such as aluminum, magnesium, or beryllium, the induced activity will be determined primarily by the impurities present; hence the estimates of induced activity must be made on the basis of known impurities or alloying elements such as manganese, zinc, cobalt, and rare earths.

In selecting materials for reactor use, the effects of reactor radiations upon the material must also be considered. The effects of radiation upon metals are somewhat like those produced by cold work or by solid-solution hardening, although neither analogy is complete. Metals are much less sensitive than organic compounds. Radiation damage generally can be considered a trivial factor in the selection of structural metal for a low-power, low-neutron-flux research reactor, while under the same conditions radiation damage can be a deciding factor in the selection of organic materials such as plastics used for electrical insulation, oils used for lubrication or insulation, and elastomers used for gaskets. A number of references touching upon the engineering implications of radiation damage and introducing this complex problem are listed in the bibliography.

In addition to the previously mentioned physical, mechanical, and nuclear properties, a reactor structural material should possess adequate corrosion or oxidation resistance in the selected coolant, adequate creep strength, impact strength, and suitable formability and joinability. It is hoped that the following comments will help to supply such information about the metals listed in Table 1. It is obviously impossible to give an adequate description of properties such as corrosion resistance, creep or formability in a single sentence (or in any form short of a thick handbook of data), but these descriptions should help in a quick comparison of the more outstanding characteristics.

Some of the metals and alloys discussed here are classified as strategic metals subject to governmental restrictions.

Aluminum

Well-established technology of aluminum greatly simplifies engineering design. Excellent formability; available at present in large supply at low cost in wide variety of forms. Good nuclear properties. Corrosion resistance and strength good at low temperatures. Low melting point and strength properties limit use to low temperatures. Excellent heat transfer. Casting alloys and high-strength wrought alloys available, some of which (based on alloying elements) have good nuclear properties.

Beryllium

Excellent moderator (see following section), very low neutron absorption. Very high cost; order-of-magnitude reductions in cost seem unlikely in view of intrinsically

expensive processing requirements. Very poor ductility with dubious prospects for major improvement as a result of further purification or alloying. Ductility greatly improved at elevated temperature (e.g., 25% elongation at 400° C). Appears promising in corrosion resistance to water at moderately low temperatures and possibly to liquid metals at high temperatures. Health hazards introduce special techniques in handling. Available in tonnage lots from several producers.

Magnesium

Light, low-cost metal commercially available as pure metal, as casting alloys, and in various extruded or wrought forms. Good strength-to-weight ratio. Excellent low value of thermal-neutron absorption cross section. Corrosion resistance in water relatively poor; not recommended for use in water above 35° C. Corrosion resistance and low melting point preclude application in reactors operating above room temperature. Many grades highly susceptible to stress-corrosion cracking. High notch sensitivity in commercial grades. New alloys containing zirconium show improved mechanical properties and much better corrosion resistance than standard alloys, but are not significantly better in corrosion resistance than high-purity magnesium.

Molybdenum

Highly refractory metal, excellent strength with good ductility up to temperatures above 1,000° C. Highly susceptible to oxidation in air above about 400–500° C. Surface cladding with nickel or Inconel shows promise of providing oxidation protection to about 1,100° C providing integrity of coating at joints such as welds can be obtained. Excellent resistance to attack by liquid-metal coolants provided oxidation is prevented. Thermal-neutron absorption low when compared with other highly refractory metals or alloys. Easily fabricated, good machinability and formability under proper conditions. Brazing techniques giving tight, nonbrittle joints are available; welding is more difficult but shows good promise. Potential supply as of 1950 greatly exceeded demand. Commercially available in ingots up to about 1,000 lb or in various forms such as plate, sheet, tubing, forgings. Several high molybdenum alloys (e.g., Mo-Ni) show considerable promise in improving high-temperature mechanical properties while retaining ease of fabrication.

Nickel

Tough, moderately strong metal well-known in the chemical industry for its corrosion resistance under extreme conditions (as a container for fused caustic, molten salts). Oxidation resistance very good (800 to 850° C for A-nickel and above 1,000° C for L-nickel). Impact strength very good (about 200 ft-lb for Charpy V-notch test). Several high nickel alloys, originally developed for high corrosion resistance in chemical process industries, possess excellent high-temperature creep and stress-rupture properties. High-temperature strength properties of the Hastelloys and Inconel X are summarized by Clark (*26*). Neutron absorption cross section of nickel and high nickel alloys higher than that of the austenitic stainless steels.

Tantalum

Very high neutron absorption practically precludes application in thermal reactors. Extremely refractory, but has a high affinity for practically all gases at elevated temperatures. The author is not aware of any successful surface coating techniques which might permit reactor applications at high temperature. Fabricability and machinability excellent. High cost combined with other disadvantages implies limited utility as a reactor construction material. Some of these remarks also apply to the chemically similar metal niobium (columbium) which also is very expensive and in critical demand as an alloying element in steel and special alloys.

Titanium

Possesses an excellent combination of mechanical strength and corrosion resistance. Satisfactory in creep, short-time hot tensile, and stress-rupture testing up to about 425° C (0.15% creep per 10,000 hr at 427° C and 16,000 psi based on 1,125-hr test) or at higher temperatures with corresponding decrease in load. Stable against air oxidation at temperatures up to about 700° C for extended use (1,000 hr). Extremely ductile, easily fabricated. Very good fatigue strength (80% of ultimate tensile strength). Stable against stress-corrosion cracking up to about 95% of yield strength. Cost and neutron absorption higher than for stainless steel or nickel alloys. Commercially available in a variety of shapes including sheet, rod, plate, seamless tubing. Higher strength mild alloys also available.

Tungsten

Similar to tantalum in having a neutron absorption cross section too high for thermal reactor applications, but has even better strength properties at extreme temperatures. Unlike tantalum, tungsten is very difficult to fabricate and join. In view of major difficulties in fabrication, poor oxidation resistance, high neutron absorption and high cost, use of tungsten or high-tungsten alloys as reactor construction materials seems unlikely.

Vanadium

Commonly considered a rare metal but actually more abundant than copper, zinc, lead or tin. The massive metal has only recently become available in pilot-plant quantities. Mining of low-grade carnotite ores for their uranium content should provide an increased supply of by-product vanadium. Chemical properties similar to those of niobium and tantalum: all are refractory metals difficult to reduce from the oxide; all have decided affinity for hydrogen at elevated temperature, show poor oxidation resistance at elevated temperatures.

Zirconium

Comparable in corrosion resistance to titanium; somewhat poorer in mechanical properties. In view of higher density and lower strength values, zirconium obviously cannot compete with titanium on a strength per unit weight basis. Thermal-neutron absorption cross section much lower than that of titanium, providing very significant improvement in neutron economy in thermal reactor applications. Neutron absorption higher than for magnesium or beryllium, but neither can compete with zirconium with respect to corrosion resistance or mechanical properties. Although corrosion resistance to water of zirconium is good, its oxidation resistance is poor and it must be protected from atmospheric oxidation in applications above 300–400° C. Probably suitable for use in contact with liquid sodium or NaK coolants, if oxidation by coolant avoided. Price very high, starting at an estimate of $5 per pound for

crude sponge (raw product of Kroll-process reduction). All zirconium as reduced from any of the common ores contains up to several per cent of the strong neutron absorber, hafnium ($\sigma_a = 120$ barns). To take advantage of low neutron absorption of zirconium, hafnium must be separated, which, in view of close chemical similarity of zirconium and hafnium, is difficult and correspondingly expensive chemical operation. Ductile zirconium produced either by Kroll or DeBoer process; DeBoer zirconium, involving thermal decomposition of zirconium tetraiodide on a hot filament is purer and more corrosion resistant but intrinsically more expensive, in addition to requiring Kroll (magnesium-reduced) product as starting material. Price estimates for reactor-grade metal vary over wide range, corresponding primarily to different assumptions concerning reduction method, scale of production, purity requirements. Although production capacity is being rapidly expanded, procurement of industrial quantities is difficult.

Stainless Steel

In view of tremendous initial capital investment in a nuclear reactor installation, even fairly large reductions in materials costs by selecting inexpensive grades of steel may be illusory if longer service life can be provided by higher performance grades. As a first criterion, then, grade of stainless steel to be selected is that grade promising longest trouble-free service life under conditions of temperature, stress, and corrosion anticipated. Use restricted to conditions of elevated temperature since at low temperatures aluminum is cheaper and provides better neutron economy. Consideration of strength and corrosion resistance at elevated temperatures suggests austenitic stainless steels. In welded structures resistance of stabilized grades such as AISI 321 or 347 to intergranular corrosion is a significant advantage. In comparison to zirconium, stainless steel has somewhat lower corrosion resistance at moderate temperatures and much larger neutron absorption, but has better strength properties and lower creep at elevated temperatures. In contrast to metals such as molybdenum, tantalum, titanium, zirconium and tungsten, stainless steel shows excellent oxidation resistance in air up to 900° C or higher. Austenitic stainless steels produced commercially in very wide variety of forms and have great advantage of well-established techniques of forming and joining.

TABLE 3—Moderators

Element or Compound	*A* (*gm/mole*)	*Density* (*gm/cm³*)*	*N*** (×10⁻²⁴ *atoms/cm³*)	σ_s, *epithermal* (*barns*)	σ_a, *0.025 ev* (*barns*)	Σ_a (cm^{-1})	Σ_s (cm^{-1})	ξ§	$N\xi\sigma_s$	$(\sigma_s/\sigma_a)\xi$	*Comments*
Hydrogen H_2	1.008	0.0090	0.0054	20.3	0.33	0.0018	0.11	1.000	0.11	61	H_2 gas at high pressure presents fire hazard.
Deuterium D_2	2.02	0.0180	0.0054	3.3	0.00046	2.5×10^{-6}	0.018	0.725	0.013	5,200	D_2 gas at high pressure presents fire hazard.
Helium He	4.00	0.0180	0.0027	0.8	—	—	0.0022	0.425	0.0009	∞	Notice low slowing-down-power.
Beryllium Be	9.01	1.85	0.124	6.1	0.009	0.0011	0.76	0.206	0.16	145	Good moderator.
Carbon (graphite) C	12.0	1.60	0.080	4.7	0.0045	0.00036	0.38	0.158	0.060	165	Graphite density varies.
Oxygen O_2	16.0	0.014	0.0054	3.8	0.0002	1.1×10^{-6}	0.021	0.12	0.0025	230	Low slowing-down-power.
Sodium Na	23.0	0.97	0.0254	3.0	0.49	0.012	0.076	0.083	0.0063	0.53	Low slowing-down-power.
Magnesium Mg	24.3	1.74	0.043	3.4	0.059	0.0025	0.15	0.073	0.011	4.4	Low slowing-down-power.
Aluminum Al	27.0	2.70	0.060	1.35	0.215	0.013	0.081	0.071	0.0058	0.45	Low slowing-down-power.
Beryllia BeO	25.0	2.8	0.067	9.9	0.009	0.00060	0.66	0.173	0.11	183	Good moderator.
Beryllium carbide Be_2C	30.0	2.4	0.048	16.9	0.023	0.0011	0.81	0.193	0.16	145	Good moderator.
Light water H_2O	18.0	1.00	0.033	44.4	0.66	0.022	1.47	0.925	1.36	62	Good moderator.
Heavy water D_2O	20.0	1.10	0.033	10.5	0.0011	36×10^{-6}	0.35	0.504	0.18	5,000	Good moderator.
Sodium hydroxide NaOH	40.0	2.1	0.032	27.1	0.82	0.026	0.87	0.77	0.67	26	Fair moderator; neutron loss high.
Polystyrene $(CH)_n$	17.0	1.07	0.038¶	25.0†	0.335†	0.013	0.95	0.842	0.80	62	Radiation damage a problem.
Paraffin $(CH_2)_n$	18.0	0.9	0.030‖	45.3‡	0.665‡	0.020	1.36	0.913	1.24	62	Radiation damage a problem.

* For the gases H_2, D_2, He, and O_2 an arbitrary density 100 times the density at NTP is assumed; i.e. a pressure on the order of 1,500 psi.
† Per (CH) unit.
‡ Per (CH_2) unit.
§ $\xi = 1 - [(A-1)^2/2A] \ln [(A+1)/(A-1)]$.
¶ Number of (CH) units/cm³.
‖ Number of (CH_2) units/cm³.
** Number of atoms or molecules per cm³.

MODERATORS AND REFLECTORS

The nuclear properties of a substance are of greater concern in the choice of moderators than in the choice of structural materials. The volume in the core of a thermal reactor occupied by moderator may be 20 or more times that occupied by structural materials. Thus neutron absorption in the moderator must be kept to a minimum, simply because there is so much moderator present. To slow down neutrons within a minimum distance the probability of neutron scattering must be high, as measured by the neutron scattering cross section σ_s multiplied by the atomic density N [the macroscopic neutron scattering cross section Σ_s, $(\Sigma_s = \sigma_s N)$], and the atomic weight A must be low to allow a large energy loss per collision.

Table 3 lists some of the more pertinent nuclear properties of potential moderators. The most direct measure of the ability of a material to slow down neutrons is the slowing down power $N\sigma_s\xi$, which is a product of Σ_s and the mean log energy loss per collision, ξ. The efficiency of a substance in slowing down neutrons without excessive absorption is given by the moderating ratio, the ratio of the slowing down power to the macroscopic scattering cross section. The method of averaging nuclear properties for atoms to obtain the appropriate values for their compounds has been described by R. F. Geller (*45*).

Other properties of interest such as melting and boiling points are also listed in Table 3.

Comparative evaluation of different moderators is best obtained by carrying out complete reactor design calculations for various configurations appropriate to the proposed moderators and proposed operating conditions. In a qualitative way it can be seen that a large moderating ratio allows a small fuel inventory or minimum fuel enrichment, as in natural-uranium reactors; a large slowing down power allows a small volume as required in high-power-density enriched reactors. In comparing heavy water and light water it must be remembered that the high initial cost of heavy water is to be compared not with the cost of light water but with the cost of more highly enriched fuel. The use of heavy water also introduces additional expenses in the initial construction in requiring protection against loss or contamination and exchange with H^1 compounds (such as light water).

Reflector material requirements. The nuclear requirements for a reflector material in a thermal reactor are similar to, but less stringent than, moderator requirements. Since the primary purpose of the reflector is to reduce neutron leakage losses, the importance or value of the reflector increases as the core surface-to-volume ratio increases.

The reflector may simply be an extension of the moderator beyond the region of fuel loading, or it may be a separate region of different (usually less expensive) moderator material. The reflector in reducing neutron leakage also contributes to some extent in shielding of moderate energy neutrons. Fast reactors which contain no moderator may still require a reflector region (in this case materials of large fast-neutron scattering cross section, generally high in atomic number and density).

SHIELDING MATERIALS

A summary of the problem of shielding from nuclear radiation has been given by L. A. Ohlinger (*115*); his extensive discussion of the selection of shield materials will not be repeated here. In view of the large quantities of shielding material required, the cost is generally a dominant factor in selection. A moderately low power research reactor may require 1,000 cubic yards or more of shield. (Cost considerations of course must be weighted differently in shielding a mobile reactor where minimum weight or minimum volume is imperative.)

The functions which a shield for combined reactor radiations must perform, and material capable of performing these functions, are outlined below:

1. Attenuation of fast neutrons. Most efficiently performed by elements of high atomic number through inelastic scattering of neutrons. Process produces gamma rays, so material used for this purpose should be placed close to the core to allow shielding of these gamma rays and also reduce weight of high-density material for a given thickness. Some possible elements: tantalum, tungsten, thorium, lead, iron, barium.

TABLE 4—Heavy-Aggregate Concretes*

Cement	*Aggregate*	*Density (gm/cm³)*	*Compressive strength (psi)*	*Water content (%)*	*Comments*
Portland	Sand, gravel	2.3	~3,500		Ordinary concrete, approximately $100/yd³ in place.
Portland	Barytes	3.5	~3,500	5.7	Handles like ordinary concrete except for weight, using Tennessee barytes. Cost about $150/yd³ in place.
Portland	Iron punchings	6	~5,000	3	Special techniques useful in placing; cost about $160/yd³ in place.
Portland	Barytes-limonite	3.2	~3,600	13	Standard curing techniques.
Portland	Barytes-colemanite	3.2	~2,500	8	Special curing techniques; 1% boron to reduce capture gamma rays.
Portland	Barytes-boron frit†	3.1			Similar to ordinary barytes concrete in handling.
Lumnite	Barytes-colemanite	3.1	~3,500		Special curing techniques.
Lumnite plus Portland	Barytes-colemanite	3.1	~3,000	8	Usable mix obtained for good curing at 1:1 ratio of Lumnite to Portland.

* For details see reference *124*.
† Borax fired with silica.

2. Attenuation of intermediate-energy neutrons. Most efficiently performed through elastic scattering which, for reasons of cost and efficiency, reduces the choice to one element, hydrogen (as water) as an essential component of the shield.

3. Absorption of thermal neutrons. Requires the presence of elements of high thermal-neutron absorption cross section which preferably do not yield hard capture gamma rays. Boron is the most obvious choice (as boric acid). In some cases the normal components including impurities in the shield materials may be adequate to remove thermal neutrons sufficiently, but even so the addition of boron is of value in reducing the quantity of (n,γ) radiation by screening the gamma emitters from thermal neutrons.

4. Attenuation of gamma rays. Primarily requires maximum density. For minimum weight (minimum cost) of high-density material it should be adjacent to core. However, high-density material must also be located near surface of shield to stop secondary gamma radiation created within shield. Same elements as in 1.

5. Attenuation of heat. Innermost region of the shield, in addition to being exposed to possibly high temperature of core, is heated by intense primary gamma radiation. Thus this region or "thermal shield" must protect outer regions of shield which often may have lower thermal stability. For this purpose thermal shield must be capable of withstanding thermal stress and possible corrosion if a thermal-shield coolant is required. This suggests iron, steel.

In actual reactor shields these functions are often not so simply distinguishable. For example, a single substance such as high-density concrete or a "swimming pool" full of water can fulfill all these functions.

The properties, relative merits and estimated costs (as of January, 1950) for a wide variety of shielding blocks, cements, aggregates, and boron vehicles have been reported by T. Rockwell (*110*). A considerable amount of more detailed information has also been declassified concerning cements and heavy aggregates suitable for use in reactor shields (*117–124*).

The use of an all-water shield for a low-power research reactor has been described by W. M. Brazeale (*116*). The concrete walls of the "swimming pool" are made somewhat thicker (about 3 ft) than needed structurally to allow emergency shielding in case of accidental loss of water. Since the thickness of the water shield is determined by gamma-ray tolerances rather than by neutron tolerances, the thickness of a water shield could be greatly reduced by adding only a few inches of iron or lead.

A study of the "Nuclear Reactor Catalog" (*5* and p. 65) illustrates the central importance of concrete as a reactor shielding material. Ordinary concrete is composed of a cement, a fine aggregate (sand), a coarse aggregate (gravel), and water. The most common variety of cement is Portland cement, which in addition to an acceptable water content (0.06–0.1 gm hydrogen per cm^3) and more than adequate strength ($\sim$4,000 psi in compression) has the great advantage of a well-established technology.

The density of concrete used for shielding is normally increased by using heavy aggregates such as barytes, iron ore, scrap iron, etc. A detailed report of the formulation, handling characteristics, and physical property charts has been published by Gallaher and Kitzes (*124*) on the concretes listed in Table 4. Satisfactory results with some of the special concretes required special handling and curing techniques; for details see the published reports.

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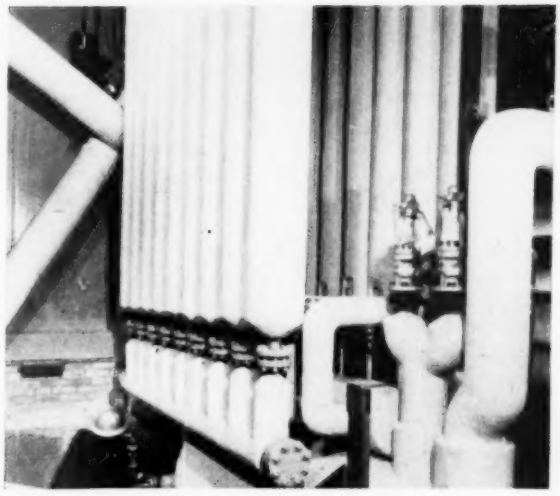
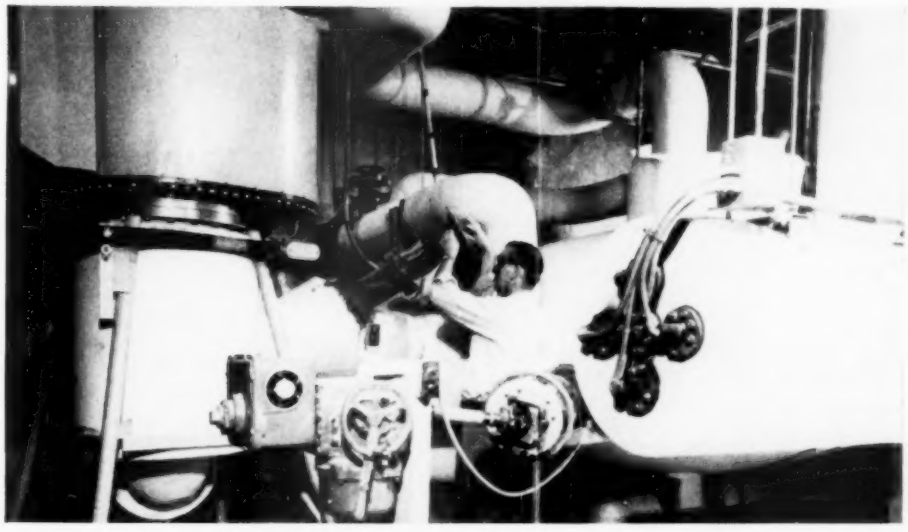
AIR INTAKE DUCT formed of cast concrete channels coolant air to Brookhaven reactor



STEAM GENERATOR of Experimental Breeder Reactor produces steam at 550° F, 400 psi



SECONDARY LIQUID-METAL COOLANT of EBR instal'ation is circulated by pump at left. Cylinder at right is heater for melting coolant after shutdown

Coolants

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ADEQUATE COOLING of a reactor core is essential for proper performance of core materials and maintenance of the integrity of the nuclear fuel. The selection of a cooling fluid and system design to accomplish this will vary considerably with the type of reactor considered.

In this discussion three types of coolants are treated—water, liquid metals, and gases. The discussion is confined to those fluids which are in use as reactor coolants or appear to have most promise for future reactors.

NUCLEAR PROPERTIES

Before discussing these coolants, their systems and components, it would be well to review their nuclear, thermal, and fluid properties as a criterion for appraising their

suitability as reactor coolants. This section discusses pertinent nuclear properties.

Nuclear cross section and moderating ratio. In selecting a coolant for a reactor, two nuclear properties of coolants must be given special consideration, namely the scattering and capture cross sections. A low capture cross section is always desirable to maintain a low loss of fission neutrons. The desired value of the scattering cross section will depend upon whether the reactor operates in the thermal, intermediate, or fast neutron range. In fast-neutron reactors, moderating properties of the coolant are undesirable, while for thermal reactors where moderation is necessary, a high scattering cross section for the coolant may be very desirable. The effectiveness of a material as a moderator may be evaluated in terms of its moderating ratio (p. 24).

Table 1 lists the nuclear properties in the thermal-neutron range of the fluids most commonly considered as reactor coolants; the only coolants possessing desirable moderating qualities are light water, heavy water, and helium. Helium, because of its very low density and resulting low macroscopic scattering cross section, will probably never be useful as a moderating coolant.

In fast reactors every effort is usually made to hold the amount of coolant or structural materials in the core to a minimum to keep neutron absorption and leakage as low as possible to reduce the critical-mass requirements. If the amount of coolant within the core is kept sufficiently low, almost any of the fluids listed in Table 1 can, in some instances, be used as coolants in a fast reactor.

While any of the fluids listed in Table 1 can be used as coolants for thermal reactors, H_2O and D_2O (because of their superior nuclear properties) are in general more satisfactory than liquid metals. Air, however, can also be used successfully for thermal reactors since its macroscopic capture cross section is quite low. A material other than air, of course, must be used as the moderator.

Neutron radiation products and half-life. If the reactor coolant under neutron bombardment forms isotopes which decay by emitting high-energy gamma rays, the shielding required around the coolant system outside of the reactor will be quite heavy. If, in addition, the half-lives of the unstable isotopes are long, the activity persists after shutdown, resulting in very limited access for long periods of time.

In this respect helium, lead, bismuth, and lithium are the most advantageous since under bombardment either no radioisotopes are formed or those that are formed emit no gamma rays. Bismuth, however, forms an alpha-emitting isotope that presents an ingestion hazard, and thus is less desirable than the others.

Sodium and potassium form isotopes with high-energy gamma rays having half-lives of 15 and 12 hr respectively. Consequently, heavy shielding of piping and components is required and accessibility for maintenance is very difficult. Oxygen in air and water forms an isotope of nitrogen which emits high-energy gamma rays but whose half-life is only about 7.5 seconds. Therefore, although considerable shielding is required during reactor operation, the activity falls so rapidly after shutdown that extended accessibility to the plant is possible in a very short time.

TABLE 1—Nuclear Properties of Coolants (*1, 2, 3*)

	Cross section		*Fractional energy loss per collision* ξ	*Moderating ratio* $\frac{\sigma_s \xi}{\sigma_c}$
	Capture σ_c *(barns)*	*Scattering* σ_s *(barns)*		
H_2O	0.6016	164 (44)*	0.918	250 (67)*
D_2O	0.000920	15.3 (11)*	0.495	8,250 (5,930)*
Na	0.45	4	0.083	0.89
K	2.5	1.5	0.03	0.018
NaK (44%K)	1.1	3.2	0.0774	0.225
Li	65	1.5	0.26	0.006
Pb	0.2	11.0	0.00962	0.529
Bi	0.015	9.0	0.00958	5.75
Pb-Bi (44.5% Pb)	0.17	9.9	0.00960	0.56
He	0.008	1.5	0.43	83
Air	1.4	8.82	0.13	0.82

* At 100 ev.

THERMAL AND FLUID PROPERTIES

Except for consideration of the nuclear properties enumerated, the requirements of a reactor coolant are similar to those of the coolant of any other heat-exchange system.

Density and specific heat. To transfer reactor heat to the external heat exchanger or steam generator effectively, it is desirable that the coolant possess a high capacity for storing heat. This capacity is determined by the product of density and specific heat. In comparison with water, the liquid metals, although of comparable density, suffer because of their lower specific heats. This is particularly true of the nonalkali metals, lead and bismuth. Gas coolants, of course, are at an even greater disadvantage because of their lower densities even at higher pressures.

Pumping power. Pumping power varies approximately as the cube of the mass flow rate and inversely as the square of the density. The flow rate, however, will increase with decreasing values of specific heat. Consequently, assuming that the flow path and amount of heat transferred per degree temperature rise are the same, a coolant with a higher specific heat and density will have a relatively lower pumping power. Among the coolants listed in Table 2, water shows the most favorable pumping power characteristics while gases are least desirable. A low pumping power is, of course, particularly desirable in a power-generating reactor plant where the power required for pumping can become a very significant portion of the entire reactor output.

Heat-transfer coefficient. The importance of a high coolant heat-transfer coefficient is apparent when one considers the high specific power inherent in the nuclear reaction. For a given heat flux a higher coefficient permits either a reduction in heat-transfer surface or a lower operating temperature difference; a reduction in either is desirable in the design of a reactor for power generation. Higher coefficients have similar effects on the design of the steam generator or external heat exchanger. For mobile reactor plants where high power output per unit weight is desirable, higher coefficients are particularly important.

In Table 2 are listed magnitudes of heat-transfer coefficients obtainable for the various coolants considered in this

article. As can be seen, liquid metals have a distinct advantage due principally to their high heat conductivities. Satisfactory coefficients can be obtained with water in the full range of temperatures for which it is considered a practical coolant. To obtain a reasonable coefficient, heat-transfer surface, and temperature difference with a gas coolant, extremely high fluid velocities are necessary.

Boiling point and vapor pressure. For coolants that are gaseous at atmospheric pressure and temperature, consideration of the boiling point and the vapor pressure is of no significance. A high boiling point and a low vapor pressure for a liquid coolant are highly desirable so that a low-pressure, high-temperature system can be designed. Table 2 shows that liquid metals have very high boiling points and low vapor pressures compared to water. Consequently, for power-producing reactor plants that require reasonably high temperatures, water-cooled reactors will involve high-pressure piping and vessel designs in contrast to the liquid-metal plant.

Melting point. Consideration of melting point as a criterion for selection of a coolant is necessary only when one is considering the use of a liquid metal. Potassium and the alloy, NaK (56% sodium, 44% potassium by weight), fluidize at essentially room temperature. Sodium and the nonalkali metals, lead and bismuth, require preheating before becoming molten; this complicates system design.

WATER

Water has been used more extensively as a reactor coolant than any other material. The reasons for this are:

1. It is available in large quantities at low cost.
2. Relatively low pressure drops are required for flow at significant rates.
3. Water has relatively high heat-transfer coefficients.
4. There is a large amount of experience in its use as a heat-exchange medium.
5. Its high scattering cross section makes it valuable as a moderator in thermal reactors.

At the same time it has two serious disadvantages for some types of reactor designs:

1. Water cannot be used very readily in unenriched thermal reactors due to its moderately high neutron-absorption cross section.
2. When used in power reactors which must operate at relatively high temperatures, water requires high-pressure piping and vessels due to its low boiling point and high vapor pressure.

System Design

There are three basic systems that are used: the swimming pool, once-through, and recirculating.

Swimming pool. An example of the simplest system is the "Swimming Pool" reactor in the Bulk Shielding Facility

TABLE 2—Thermal, Fluid Properties of Coolants

	Water		*Sodium*	*56% Na 44% K*	*Lithium*	*Pb-Bi Eutectic*
Pressure (psia)	14.7	1,500	14.7	14.7	14.7	14.7
Boiling point (°F)	212	596.23	1,621	1,518	2,403	3,038
Freezing point (°F)	32	—	208	66.2	354	257
Density (lb/ft³) at						
100° F	62.0	—	—	56.1	—	—
500° F	—	48.6	55.3	52.9	31.3	646
1,000° F	—	—	51.1	48.7	29.8	624
Specific heat (Btu/lb/° F) at						
100° F	0.9976	—	—	0.2733	—	—
500° F	—	1.165	0.3150	0.2583	1.000	0.035
1,000° F	—	—	0.3005	0.2486	1.000	0.035
Heat transfer coefficient* (Btu/hr/ft²/° F) at						
100° F	3,970	—	—	7,870	—	—
500° F	—	6,030	15,200	7,630	14,100	7,150
1,000° F	—	—	13,200	7,400	13,900	8,120
Pumping power for equivalent heat removal† per °F temp. rise at						
100° F	1.000	—	—	57.8	—	—
500° F	—	0.674	26.5	48.7	3.16	134
1,000° F	—	—	34.0	63.4	3.41	133
Pumping power for equivalent volumetric flow‡ at						
100° F	1.00	—	—	0.758	—	—
500° F	—	0.544	0.717	0.662	0.457	7.39
1,000° F	—	—	0.625	0.582	0.418	6.63
Pressure (psia)	14.7	100	500	14.7	100	500

	Air			*Helium*		
Density (lb/ft³) at						
100° F	0.071	—	—	0.00978	—	—
500° F	0.0413	0.281	1.385	0.00570	0.0388	0.1940
1,000° F	0.0272	0.185	0.920	0.00375	0.0255	0.1275
Specific heat (Btu/lb/° F) at						
100° F	0.2405	—	—	1.241	—	—
500° F	0.2475	0.2495	0.2520	1.240	1.240	1.242
1,000° F	0.2660	0.2680	0.2710	1.240	1.240	1.240
Heat transfer coefficient§ (Btu/hr/ft²/° F) at						
100° F	23.4	—	—	25.9	—	—
500° F	20.6	95.8	342	16.5	79.3	289
1,000° F	18.6	87.5	228	12.5	57.2	205
Pumping power for equivalent volumetric flow¶ at						
100° F	1.00	—	—	0.1002	—	—
500° F	0.72	3.62	13.90	0.1652	0.78	2.41
1,000° F	0.625	2.81	10.26	0.226	0.614	1.82

* Water and metal coolant coefficients determined for a velocity of 20 ft/sec in a ½-in. inside diameter tube.

† Normalized to a value for water at 100° F and 14.7 psia with a velocity of 20 ft/sec in a ½-in. inside diameter × 10 ft long tube.

‡ Water and metal coolants normalized to water at 100° F, 14.7 psia with a velocity of 20 ft/sec in a ½-in. i. d. × 10 ft long tube.

§ Gas coolants coefficients determined for a velocity of 100 ft/sec in a ½-in. inside diameter tube.

¶ Gas coolants normalized to air at 100° F, 14.7 psia with a velocity of 100 ft/sec in a ½-in. inside diameter × 10 ft long tube.

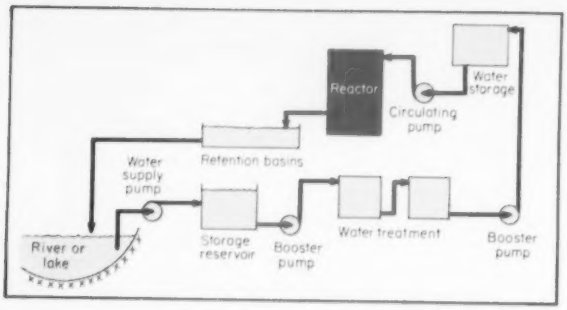

FIG. 1. Once-through water coolant system

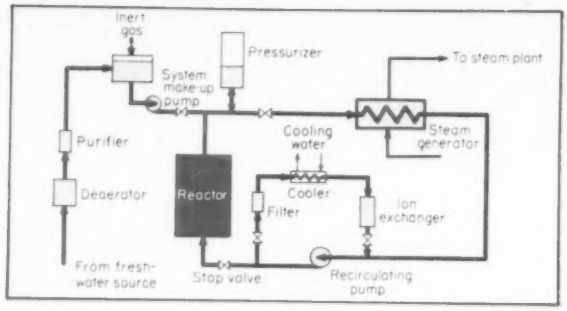

FIG. 2. Recirculating water coolant system

at Oak Ridge National Laboratory (*4*). This reactor consists of a core assembly submerged in a large pool of water which acts as coolant, shield, and moderator. This type of cooling system is satisfactory only for low-temperature and low-power reactors for research purposes.

Once-through design. Figure 1 shows the principles of this method. In the water treatment facilities living organisms such as algae are removed and suspended material is filtered out. The treatment may also consist of adding chemicals to adjust pH, and of demineralization, deaeration and cooling.

After passing through the reactor, the water must be held in retention basins until the activity induced in its impurities has decayed sufficiently to permit its re-entry to the lake or river.

This method of cooling is satisfactory for high- or low-power, low-temperature reactors but, obviously, would not be of use to power-generating reactors. The coolant in this scheme may or may not be used for moderating purposes depending upon the intended use of the reactor. For plutonium-producing plants it is necessary to hold the amount of water within the core to an absolute minimum because of its high neutron-capture cross section while, for some kinds of research reactors, it is feasible to use the coolant also as moderator.

Recirculating design. This design is used for the Submarine Thermal Reactor under development for submarine propulsion. Basically, this method of cooling is quite simple. Figure 2 shows a simple schematic of the recirculating or closed-cycle design including the more important coolant auxiliary systems. This design may be used in various types of reactors ranging from small, low-power, low-temperature research facilities to high-power, high-temperature power reactors.

The recirculating system has the following favorable characteristics:

1. Water handling facilities can be held to a minimum since neither large storage reservoirs, retention basins or water-treatment facilities are needed.
2. It is the only practical design for a water-cooled power-generating reactor plant.
3. Induced reactivity is confined to a closed system.

With a recirculating system steps must be taken to keep the impurities in the water at a very low level to prevent radioactivity of the coolant from rising to a high equilibrium value. A high coolant activity will result in an accessibility problem as well as the possibility of increased shielding thickness. High levels of impurity in the coolant are also undesirable because of possible fouling of heat exchange surfaces.

To hold impurities in the coolant to a low level, it is necessary that the materials used in the system do not corrode excessively. For low-temperature service, aluminum is frequently used as a piping material but, at high temperatures, it has been found necessary to use the 300 series stainless steels and a few other highly corrosion resistant materials such as Inconel and K Monel. In addition to the use of corrosion resistant materials, it is necessary to include a purification system to remove foreign material continuously from the coolant. The system shown in Fig. 2 consists of a filter to remove suspended material and a demineralizer to remove dissolved solids. In high-temperature plants it is necessary to include a heat exchanger in the demineralizer inlet line since the resins, which are the active substances in the demineralizer, cannot withstand temperatures much in excess of 120° F.

Precautions must also be taken in the treatment of the filling and make-up water for the recirculating system to maintain high purity. This water must be purified by either distillation or demineralization (or both) and must also be deaerated. The purpose of deaeration is to remove all corrosion-accelerating gases, particularly oxygen which has very adverse effects on materials containing high-temperature water. After treatment, stored make-up water must be protected from the atmosphere by an inert-gas head.

In some instances, it may also be desirable to add substances to the coolant to reduce the corrosion rate. Needless to say, any corrosion inhibitor must not become excessively radioactive under reactor radiations, and at the same time, it should not be readily absorbed by the demineralizer if demineralization is still necessary. These two requirements severely restrict the number of materials which can be used as corrosion inhibitors.

Another essential feature of the recirculating water system is a pressurizer to create and maintain the desired system pressure. The pressurizer normally consists of a tank, connected to the main circulating loop by a surge pipe, containing either steam or a noncorrosion-accelerating gas over a free water surface to develop system pressure. This compressible vapor or gas volume also tends to stabilize system pressure during coolant volume changes caused by temperature fluctuations. A steam head may be maintained in the pressurizing tank by electric heaters located in the tank, while a gas head may be achieved by connecting the tank to a source of high-pressure gas.

On some plants it may be desirable to incorporate a degasifier in the coolant system to remove gases formed either by corrosion or dissociation of water by nuclear radiation in the reactor. Degasification can be accomplished in a steam-head pressurizer by spraying a small

amount of coolant into the steam space and removing the separated gases with some steam through a throttled vent.

Heavy water. The low absorption cross section and high moderating ratio of heavy water make it possible to build a thermal reactor using only natural uranium with a recirculating coolant system. The high cost of heavy water necessitates prevention of leakage, handling losses, or dilution by light water in the atmosphere (*5*).

Homogeneous reactors. The system design for water-cooled homogeneous reactors is basically the same as for heterogeneous reactors. In designs in which the fuel is dissolved or suspended in the coolant, however, the shielding and accessibility problems are much more severe due to the high activity of the mixture. In place of a purification system, a method of removing fission products is required which, in the case of the High Power Water Boiler at the Los Alamos Scientific Laboratory (*6*), is accomplished by an ether extraction process. Dissociation of water is rather high in homogeneous reactors; a degasifier or gas recombiner is required. Leakage from the system is extremely serious due to the low permissible ingestion tolerance. Material specifications must also be very rigid since the corrosion rate will be a function of temperature and the type of fuel solution used.

Components

For once-through coolant systems conventional components such as those in the power and process industries can be used, but the very low permissible leakage of recirculating water-cooled reactors (because of radioactive impurities) results in somewhat different designs.

Vessels, heat exchangers, and instrumentation are built along rather conventional lines except that all-welded construction is used. Heat-exchanger tubes are both rolled and welded into tube sheets. Where flanges are used for reasons of parts replacement or inspection, seal welds must be incorporated in their design.

To prevent leakage through packing on pump shafts, the pumps and their drive motors are contained within a single welded assembly with the rotor immersed in the coolant and supported by water lubricated bearings (*7*, *8*). The coolant is confined by a thin nonmagnetic metal "can" located in the gap between the rotor and stator.

Stem leakage from valves may be prevented in a number of ways such as using bellows seals or operating the valves by "canned" motors or coolant-operated pistons. Piston-operated valves require the additional complication of remotely operated solenoid pilot valves to direct the motion of the piston and "canned" motor booster pumps to provide the needed differential operating pressure.

LIQUID METALS

The principal advantages resulting from the use of liquid metals in reactor cooling systems are the high temperatures at which they can operate and the high heat-transfer coefficients that can be realized in the heat-exchange equipment. Both are of particular interest if the reactor heat is to be converted to useful power.

Experience in the use and handling of liquid metals in applications by the chemical, petroleum, metals, and allied industries is available (*3*). Because of their apparent advantages as reactor coolants, the development of liquid-metal technology, particularly that of sodium and sodium-potassium alloys, has received added impetus in the past five years (*9*). Examples of their application to reactor cooling systems are the Experimental Breeder Reactor and the Submarine Intermediate Reactor.

To date greater emphasis has been placed on the use of the alkali metals, sodium and an alloy of 56% sodium, 44% potassium by weight. Experience in the use of these metals in experimental heat-transfer systems of ratings up to 7×10^6 Btu/hr at temperature to 950° F is available (*10*).

Experience with lithium has been limited to a few experimental loops. Besides possessing a rather high absorption cross section and a high melting point, it is the most chemically active of the alkali metals.

The nonalkali metals, lead, bismuth, and lead-bismuth alloy, while considerably less hazardous in their chemical reactions, have not received similar attention because:

1. The low specific heats of these metals require high flow rates for heat removal.
2. Materials corrosion data for these metals are incomplete and, in many cases, conflicting.
3. These materials have higher melting points than the alkali metals.

System Design

With a sodium or sodium-potassium-alloy system, temperatures to 1,000° F are feasible with low system operating pressure. Materials used in the construction of these systems will depend on the system operating temperature and the resultant corrosion problems. For temperatures to 450° F ordinary carbon steel is considered acceptable; for higher temperatures to over 1,000° F the ferritic and austenitic stainless steels as well as nickel and nickel alloys with iron, chromium and molybdenum may be usable.

To obtain reduced corrosion rates and avoid plugging of restrictions in the system, a high degree of purity of the metal coolant is required. Precleaning of the system prior to filling, plus care in the handling, filling and draining operations, are necessary to maintain a high degree of purity of both coolant and system.

Safety requirements. It is essential that the system assembly be absolutely leakproof to avoid the fire and toxicity hazards inherent in the use of alkali metals. Proper welding procedure, piping design and extensive leak testing are imperative.

Since the alkali metals react explosively with oxygen and water vapor, an inert gas such as nitrogen, argon or helium is required as their blanketing atmosphere. It is necessary that the gas used for this purpose be free from impurities that might contaminate the metal coolant. The degree of purity required depends on such factors as the required liquid-metal purity, the amount of gas employed, and the expected life of the system.

For an installation of this type adequate provision for safety must be provided in the design of the system and auxiliary facilities. These should include means of minimizing the possibility of a chemical reaction should leakage occur, confining the spread of metal from a leak, controlling ventilation for the area, and providing adequate fire-control equipment.

Care must be exercised in the selection of thermal insulation for use with these systems since many conventional insulators react violently with sodium or sodium-potassium alloy in an air atmosphere.

Preheating. The melting points of these metals, while quite low by usual standards, are still higher than normal ambient temperatures. This requires that a means of preheating and maintaining the metal molten be provided

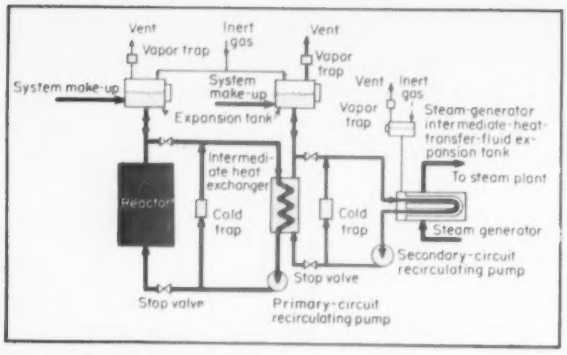

FIG. 3. Binary liquid-metal coolant system

when the system is not in operation. This is done by providing a low heat-input flow to the coolant throughout the whole system. Electrical resistance heating by wire, strip or rod heaters has been found satisfactory.

Binary heat-exchange system. The essential elements of a liquid-metal system are depicted in Fig. 3. This schematic shows a recirculating binary system for power production. The primary and secondary systems are separated by the heat-transfer surface in the intermediate heat exchanger, and each is provided with its own auxiliary systems. Each circuit is also provided with an expansion tank exposed to an inert gas atmosphere to accommodate coolant expansion under temperature variations and to supply system make-up. Coolant purity is maintained by causing a small amount of the total system flow to bypass through a cold trap. In this low-temperature bypass the liquid metal is cooled to just above the melting point where oxides precipitate out because of their reduced solubility at the lower temperature and are removed by filtration.

If it is desirable to use a single coolant system, the intermediate heat exchanger can be replaced by the steam generator and the secondary circuit and its auxiliary systems and components eliminated. The principal advantage of a binary system accrues from confining the radiation induced in the coolant in passing through the reactor to a smaller system, minimizing the hazards of a radioactive leak to the steam system, and from a possible shield weight reduction in that shielding is needed for the primary circuit only. In choosing a design, these advantages must be weighed against the added systems, components, and lower coolant temperatures available for steam generation that result from a binary system.

Components

Special consideration over and above established practices is necessary in the design of components for liquid-metal systems. The high degree of coolant purity required, the necessity that the system be leaktight, and the high melting point of the coolant add to the difficulties of component design. On the other hand, the metallic properties of the coolant permit a unique design of pumps, instruments and auxiliaries.

Valves employing bellows seals and metal-to-metal seats have been used successfully in liquid-metal systems. As in the construction of the system itself, proper welding procedure and leak testing is essential to successful design. As a precaution against bellows failure a double-bellows design with an inert-gas atmosphere between bellows and provision for leak detection has been used.

For alkali-metal heat exchangers where the secondary fluid is to be water or steam, care must be taken to avoid the possibility of a chemical reaction with the metal coolant. Designs of this type, to date, have employed a double tube construction, either concentric tubes or adjacent tubes, with the annulus or void between tubes filled with an intermediate fluid to promote heat flow between tubes. The schematic, Fig. 3, illustrates this type of construction in the steam generator. Since the intermediate fluid remains stagnant, good heat conductivity is an essential requisite of this fluid. Mercury has been used successfully in this capacity. Both evaporators and superheaters for natural and controlled circulation of this type have been fabricated and operated successfully for a number of years in experimental systems delivering 6,630 lb/hr of 450 psig, 650° F superheated steam (*11*).

Pumps. The development of pumps for liquid-metal systems, particularly for sodium and sodium-potassium alloy, has received increasing impetus. A centrifugal pump with a long overhung shaft and inert-gas seal of 400-gal/min and 126-ft head rating has been operated successfully for several thousand hours at a temperature of about 750° F (*12*). Canned-rotor pumps have been used in circulating sodium-potassium alloy at temperatures to 1,100° F with some success, but wear and galling of bearings in a liquid-metal atmosphere remains a considerable problem (*3*).

The high conductivity of some liquid metals, particularly sodium and sodium-potassium alloy, enables the use of induced electromagnetic forces as a means of circulating the fluid. Both d-c and a-c conductor or Faraday pumps have been developed (*13*). The low voltages and high current requirements of the d-c type preclude their use in large systems. Pumps of this type have been developed for capacities of 400 gal/min and 100 ft heads. Bulky magnetic circuits and low efficiency (~15%) limit the use of the Faraday a-c pump to small systems.

A number of induction type electromagnetic pumps have been developed (*13*). These are of two general types—the helical flow and the linear flow. The helical flow appears best suited for high-head, low-flow systems. Pumps of this type have been built which develop heads of 260 ft and flow rates to 400 gal/min with efficiencies of 15–20%. The linear induction pump appears best suited for applications where large flows at moderate heads are required. Pumps of this type have been built with capacities of 1,200 gal/min for a head of 110 ft with efficiencies of about 35%.

Generally speaking, electromagnetic pumps are much less efficient and are larger than mechanical pumps of comparable rating. They do, however, permit a design where bearings and seals are avoided and leaktight operation is assured.

Instrumentation. The design of instrumentation for liquid-metal systems must take cognizance of the general systems design requirements mentioned previously. Avoiding the plugging of small lines and instrument restrictions has proved troublesome in the past. Conventional temperature-detecting devices have proved satisfactory for liquid-metal service. Standard pressure-detecting devices can be used, but more reliable performance is obtained if a buffer of inert gas is used between the metal coolant and the pressure-sensing element.

Liquid-metal flow can be measured satisfactorily with rotameters. The use of orifices for flow measurement has not proved satisfactory because of the difficulty of obtaining precise pressure-drop measurements. Magnetic flow meters have been developed, but their performance has not been

completely satisfactory. They tend to drift, are slightly affected by temperature, and are dependent on the pipe surface being wetted. For level indication, buoyant-type indications have been found satisfactory. Impedance- and resistance-type electrical level indicators have been developed. Of the two, the resistance type appears more satisfactory (*3*).

GAS

Gas-cooled reactors constructed to date have used air as the coolant and have been intended primarily for research purposes. The cooling air temperatures for reactors of this type, such as those at Brookhaven, Oak Ridge, and Harwell, are relatively low and are not intended to produce useful power.

A logical high-temperature application of an air-cooled reactor would be for aircraft propulsion. The present elements of a conventional aircraft gas turbine could be retained with the exception that the combustor used for heating the air stream would be replaced by a reactor.

A second high-temperature application for a gas-cooled reactor is for the generation of electric power. By incorporating a gas-cooled reactor into a closed-cycle gas turbine plant, a power plant of reasonably simple design and of relatively low space and weight requirements could be obtained. Helium for this application would be especially desirable because of its relatively good heat-transfer properties, freedom from corrosion problems, and desirable nuclear properties.

System Design: Open System

For reactors operating at relatively low temperatures, atmospheric air cooling has certain advantages, including: simplification of the cooling system, employment of conventional equipment, and minimized corrosion problems due to the coolant itself.

Of course, there are disadvantages to the use of air cooling, including: large equipment size (blowers and ducting) because of the very low density of air at atmospheric pressure, rather high power requirements for circulating the air, low heat-transfer coefficients, and dispersal of the radioactive air discharged from the reactor.

The design of an open system for an air cooled reactor is relatively simple, as may be seen from the schematic diagram, Fig. 4. Filters on the inlet side of the reactor remove dust particles from the cooling stream to prevent fouling of the reactor heat-transfer surfaces as well as to prevent overloading of the filters mounted on the discharge side of the reactor. The cooling stream next passes to a suitable plenum chamber where the air flow is distributed to the various cooling channels in the reactor to remove heat generated in the fuel elements.

After being discharged from the exit plenum chamber of the reactor, the air is drawn through a second filter at which point radioactive material picked up during passage through the reactor or passed by the inlet filter is trapped out of the air stream. After passing through the exhaust blower downstream of the reactor and exhaust filter, the air is discharged into ducts leading to an exhaust stack where the radioactive cooling air is dispersed into the atmosphere. The blowers are located downstream of the reactor so that the pressure inside the reactor is below the ambient pressure, thereby preventing leakage of radioactive air into the immediate surroundings. The principal concern, from the standpoint of a radioactive hazard, is not the oxygen but

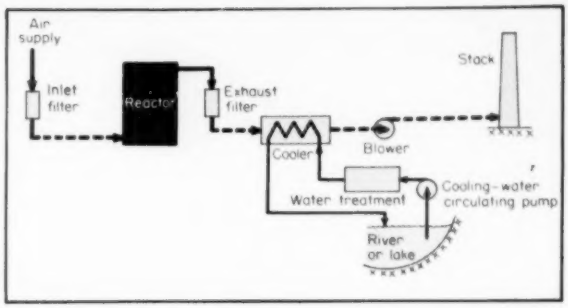

FIG. 4. Once-through air coolant system

the argon in air which has a relatively long half-life of nearly two hours (*14*).

For a design in which large amounts of power must be dissipated, it is probable that two or more parallel ducts to the blowers, as well as several blowers in parallel, will be required. For such a case dampers in the ducting would be needed to balance the flow resistance in each path, and valves to isolate each blower would be required so that repair work could be conducted without shutting down the entire reactor cooling system.

To reduce the physical size of the duct work and the blower as well as the temperature at which the blower is required to operate, a heat-exchanger may be incorporated into the cooling system ahead of the blowers. Conventional finned-tube air-to-water heat exchangers may be used with cooling water supplied from any convenient source such as a lake or river. Water treatment facilities, depending upon the quality of the water source, must be supplied to prevent fouling of the heat exchanger by the cooling water.

If the reactor operates at a sufficiently high power level for reasonably extended periods, the above auxiliary cooling system may be utilized to supply hot water for the heating of the site buildings; this has been done at Harwell (*15*).

In large installations the noise level resulting from blower operation and from the high air velocities in the duct work may become a problem. For such cases it will be necessary to install sound-absorbing devices in the duct work.

System Design: Closed System

The following advantages result with a closed-cycle gas-cooled reactor for power production: minimized corrosion problems due to the coolant itself, elimination of fouling of compressor or turbine blading as well as heat-exchange surfaces, and utilization of component design experience of the gas-turbine industry.

The following disadvantages are seen for a gas-cooled reactor for power production: supply problems with use of high-pressure helium unless seal leakage is held to an absolute minimum, high pumping power even at elevated pressures, heat-transfer coefficients relatively low even at high pressures, and moderately high system pressures.

Although there are no known gas-cooled reactors constructed to produce useful power, the possibilities of such a design are attractive. The basis for a reactor plant of this type is found in the design of the Escher Wyss-AK closed-cycle gas-turbine plant (*16, 17, 18*). This plant is illustrated schematically in Fig. 5. Gas is compressed in a two-stage compressor with an intercooler between the two stages, and is passed through a regenerative heat exchanger prior to entering the reactor. Heat picked up at this point

from the exhaust of the low-pressure turbine reduces the heat rejected from the system and increases the efficiency of the cycle.

From the regenerator the gas flows through the reactor, absorbing additional heat, and then passes to the high-pressure turbine where it is partially expanded. Further expansion occurs in the low-pressure turbine from which it is exhausted to the regenerator. The temperature of the partially cooled gas is further reduced by the precooler placed ahead of the first stage of the compressor, at which point the cycle is completed.

Control of the power output may be accomplished by raising and lowering the pressure level in the system, thus altering the density of the gas and consequently its heat removal capacity. To increase power, gas is introduced into the system from the high-pressure accumulator, while to decrease power, gas is bled from the system to the low-pressure accumulator. Of course, additional controls are required to permit the reactor to follow the power demand of the plant.

By using helium, which is an inert gas, as a coolant, two advantages result:

1. The coolant will not become radioactive by passage through the reactor. Consequently, the shielding for the coolant circuit external to the reactor will be held to the minimum. However, the possibility of impurities in the gas and pickup of impurities from the system will undoubtedly necessitate some shielding and a small by-pass flow through a filter for purification purposes.

2. The corrosion problem will be virtually eliminated, even for high-temperature applications. For components external to the reactor, high chromium molybdenum steels and the 300 series stainless steels would be suitable.

For helium, system make-up from storage tanks must be provided inasmuch as the shaft seals for the rotating machinery will undoubtedly experience some leakage. Because of the supply problem for helium, this leakage must be minimized.

Use of the closed-cycle gas-turbine principle with elevated pressures results in considerable reduction in equipment size, giving a compact plant design. The single circuit in a plant of this type also contributes to an appreciable size reduction as compared with the multiple circuits required for other coolants in reactors for power production.

Components: Open System

For air-cooled open systems there are few component development problems. Experience is available in the power-plant and heating, ventilating, and air conditioning fields to supply designs for the necessary equipment. Materials of construction for the components can be carbon steel or the other usual metals for low-temperature service.

Centrifugal blowers for air circulation are similar in design to those used in power-plant work and are available commercially.

Heat exchangers, if required to cool the exit air stream, can be of conventional design using externally-finned tubes to reduce the surface area. These units would be similar in design to the economizers used in steam power plants.

Mechanical filters on the inlet side of the reactor can be standard design, although those for the discharge side would have to be constructed of glass cloth or equivalent to withstand the high temperatures.

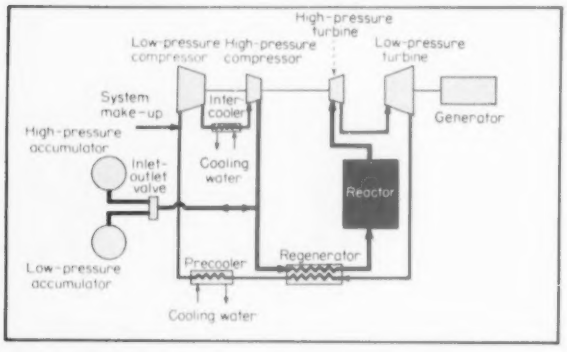

FIG. 5. Recirculating gas coolant system

Components: Closed System

Experience is available on component design for closed-cycle gas-turbine plants, although the major portion of this development work has been done in Europe. Axial-flow compressor designs, used because of the relatively high flow rates, could be evolved from existing gas-turbine plants. Gas turbines for this application represent a reasonable extension of existing designs and should not be a major problem.

Heat-exchanger design will follow practices developed by the gas-turbine industry for present installations. Because of the relatively high compressor discharge pressures as compared to open cycles, a shell-and-tube exchanger will probably be used for the regenerator.

Valves need not be used in the primary circuit except in the case where isolation of parallel circuits is required. Control valves will be needed, but designs from existing plants could be adopted for this use.

A major design problem for the closed-cycle plant will be rotating shaft seals. Leakage must be held to a minimum, and the heated gases in the turbine must be prevented from coming in contact with the oil-lubricated shaft bearings. A labyrinth design using gas from the exhaust of the high-pressure compressor as a buffer fluid has been used successfully for this application. This relatively cool gas enters the seal at an intermediate point where the flow is divided, a portion passing into the machine and the rest flowing out through the labyrinth seal to a collecting space between the seal and bearing. Gas leakage beyond this point is prevented by an oil seal used in conjunction with the bearing. The sealing gas contaminated with oil must be collected from all shaft seals and purified before being returned to the system (*16*).

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CONTROL ROOM of homogeneous reactor at Oak Ridge

Reactor Operation

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THE FUNDAMENTALS of the various methods of nuclear reactor control have been made available in the published literature (*1, 2*). All important information about the performance of the reactor and its auxiliaries is channeled to a central point from which the reactor system can then be controlled by one operator. To make this centralized control possible, many commercially available instruments, measuring circuits, mechanisms, and devices are used. The assembly of this equipment is called the Reactor Control System; it is tailored to fit the needs and desires of the operating force charged with obtaining suitable reactor performance. The various components of such a system are described in the following pages.

NEUTRON DETECTORS

The reactor average neutron density or flux is measured by neutron detectors located in the reactor shield, where, normally, the flux ranges from 1 n/cm²/sec to 5×10^{10} n/cm²/sec. The neutron-sensitive material is B^{10} or U^{235}, coated on the electrodes, or a BF_3 gas filling. For coated-electrode chambers the gas filling may be argon, nitrogen, helium or air at one to two atmospheres pressure. The electrodes are usually made of pure iron, 28 aluminum, or brass, the chamber housing being stainless steel, aluminum or brass. Electrode supporting insulators, with resistance upwards of 10^{15} ohms, are usually made of quartz or lavite. Kovar-to-glass sealed units rated to several thousand volts, commercially available, are used to bring connections through the sealed housing and to support electrodes.

Ion current chambers and counting chambers are normally operated at 20–40° C, but may be constructed to withstand higher temperatures. Current chambers deliver about 10^{-14} amp/unit flux and are used in fluxes which give a maximum current output of about 100 μa. The present trend is toward the use of higher sensitivity chambers at maximum current output approaching 0.5 ma.

Neutron detectors can be divided into essentially two classifications, low flux range (less than 10^4 n/cm²/sec) units called pulse or counting chambers which are used for start up and reactor core assembly and which are removed for normal operation, and normal flux range (above 10^4 n/cm²/sec) units called ion current chambers which are used to operate the reactor.

Proportional pulse chamber (*3*). Used to measure low-level neutron flux up to 10^4 n/cm²/sec in presence of gamma radiation up to 10^2 r/hr by incorporating, in pulse counting circuit, pulse-height discriminator that discards smaller pulses due to gammas. Has small center electrode; resulting high field strength used to obtain gas amplification within chamber. Commercially available in many designs, usually with B^{10}-coated electrodes. Used up to about 100,000 cps; sensitivity about 4 cps/unit flux.

Fission pulse chamber (*3*). Used for measurement of neutron flux from 10 to about 10^5 n/cm²/sec in presence of gamma intensity as high as about 10^5 r/hr corresponding roughly to 2-Mev gamma flux of 10^{10}/cm²/sec., by providing pulse-height discrimination in counting circuit. Usually specially constructed for particular application. Elec-

trodes coated with uranium oxide. Sensitivity about 1 cps/unit flux.

Ion current chamber. Neutron-sensitive chambers (*3*) used to measure reactor neutron density; generally operated in neutron flux above about 10^3 n/cm²/sec although useful below this flux if currents due to background radiation are absent. Commercially available with boron-coated sensitive elements; will deliver about 5×10^{-15} to 5×10^{-14} amp/unit neutron flux at saturation voltage of 100 to 500 volts. Chambers with uncoated electrodes available for filling with BF_3 gas—will deliver upward of 5×10^{-14} amp/unit neutron flux at saturation voltage of 500 volts or more. Capacity normally 50–200 $\mu\mu$f. Units constructed for special applications, BF_3 gas filled or with boron- or uranium-coated elements, built in sizes from ½ in. to several inches diameter, various lengths. For linear operation over more than three decades of flux, chambers constructed with closely spaced (¼ in.) coaxial-cylinder or flat-plate electrodes.

Compensated ion current chamber. Used to measure 10^4 to 10^{10} n/cm²/sec in presence of about 10^5 r/hr gamma radiation. Commercially available upon special order; usually designed and fabricated to meet specific conditions. Sensitivity normally about 10^{-14} amp/unit flux. Basically two current chambers in single enclosure, one neutron sensitive (B^{10} coated) and both gamma sensitive, electrically connected in current opposition for gamma-current cancellation (*2*). Saturation voltage for typical units between 500 and 1,000 volts at 10^{-4} amp output.

Neutron thermopile. Used to monitor flux above about 10^{10} n/cm²/sec in space-restricted locations in reactor core or reflector. Compact units of an even number of thermocouple junctions assembled and connected in series electrically; alternate junctions coated with a neutron absorber (boron or uranium) by mixing absorbing material with good commercial adhesive (*4*). Commercial thermopile assemblies used by coating junctions. Assembled units about ¼ in. in diameter and several inches long; may be designed to meet many special requirements. Time constant about 4 sec; about 10^{-11} volt/unit flux.

INDICATING INSTRUMENTS

A variety of pulse or current measuring channel assemblies can be used with both the low and normal flux range neutron detectors. In the normal flux range (above 10^4 n/cm²/sec), commercial units used are essentially low-value current measuring devices with an input impedance from 500 ohms to several megohms. Selection of a particular device is based upon reliability, accuracy, range of operation and ion chamber or source impedance. The dynamic impedance of the ion chamber can be defined as the ratio of the change in voltage to the change in current of a chamber operating in a given flux, or delivery of a given current with a particular voltage applied to the electrodes, the values being established by test. The saturation voltage rating of a chamber is normally that value of applied voltage at which dynamic resistance is 10^9 ohms or more.

Pulse amplifier. Used to amplify the signal from pulse chamber. Sometimes referred to as a linear amplifier, since pulse shape at output is good reproduction of the input pulse (*3, 5, 6*). Frequently specially designed to meet needs of a specific proportional-counter application; includes provision for pulse-height discrimination. Commercial units available with 1-μsec resolving time; usually include in compact unit a decade count register, mechanical register, linear power supply, and provision for observing pulse on an oscilloscope.

Electronic counting register. Used to record number of pulses at output of pulse amplifier and to provide power to drive mechanical register. Composed of electronic flip-flop units; commercially available as binary scalers to 64 counts or by decades to six digits.

Mechanical register. Used to extend range of electronic register. Electromagnetically-operated rotating-disk counters of four or more digits designed for use with radiation counter circuits commercially available. Typical units require 10 ma to operate magnet which has 1,000 ohm d-c resistance, 3–4 henries inductance, limiting rate to 10 cps. Usually used at 5 or less cps.

Pulse counter. Used to count and record pulses from pulse amplifier. May include voltage discriminator, electronic register, mechanical register (*7*).

Timer. Used with counters to compute counting rate; supplied as integral equipment on commercial pulse counters. Also used to measure period of reactor flux change as shown by galvanometer or micromicroammeter.

Chronoscope. A high-speed timer, commercially available, measures time intervals between 0.01 msec and 3 sec. Typical uses: timing interval between successive limit-switch operations on safety rods; checking for free rod operation; measuring contact opening time of relays, switches; timing other fast acting units.

Counting-rate meter. Used to indicate continuously number of cps (*8*) as measured by pulse counting chamber. Consists of multivibrator, averaging circuit and output meter, usually 0–1 ma calibrated in counts/unit time, and outlet for attaching commercial 0–50 mv recorder. Commercially available units cover range up to 10^6 cps.

Galvanometer. Used to measure current from ion chamber. Commercially available light-beam type usually used, having 500-mm scale to obtain good scale resolution, sensitivity of about 5×10^{-10} amp/mm, impedance of 500 ohms, and period of 6 sec. Suited to reactor use because battery supply for ion chamber and galvanometer light will make reading of reactor flux available over a long period of time, independent of interruptions in public-utility power service. Principal disadvantage: difficulty of maintenance and ease of damaging suspensions.

Ayrton shunt. Used to change sensitivity of galvanometer and maintain critical galvanometer damping. Commercially available shunts usually used, but special attenuators for greater range of sensitivity adjustment may be constructed using commercially available switches with shorting-type low-resistance contacts, and wire-wound resistors supplied by the manufacturers to accuracy of $\pm \frac{1}{4}\%$ of specified resistor value.

Vibrating-reed electrometer. Used to measure current from ion chamber in place of galvanometers or electronic amplifiers. Commercially available units used with input resistors of 10^{11} ohms to measure as low as 10^{-13} amp for full-scale deflection of output meter. Have desirably stable operating characteristics, due to use of a-c amplifiers. Output displayed on a millivoltmeter or chart recorder. Commercial units also can give full-scale deflection for a 10^{-4} volt input signal, thus are suitable for use with neutron thermopiles and thermocouples.

Electronic amplifier. Used to amplify voltage signal developed by passing ion-chamber current through resistors of 10^7–10^{13} ohms at amplifier input; usually constructed to give full-scale deflection of output meter with 10^{-12} amp at

maximum sensitivity. Feedback used for stability and input time-constant reduction (*9*). Output in milliamperes or millivolts displayed on commercially available meters or chart recorders.

Micromicroammeter. Used to measure current from ion chamber. Commercially available with maximum sensitivity of 10^{-9} amp for full-scale deflection; over-all accuracy of $\pm 2\%$ full scale. Output displayed on indicating meter; commercial millivolt recorder can be connected.

Millivolt recorder. Used to record output of counting-rate meter, electronic amplifier, logarithmic amplifier, micromicroammeter, neutron thermopile, thermocouple, similar low-voltage low-impedance sources in reactor instrumentation system. Commercially available to measure 1 mv full scale; 0–10 and 0–50 mv instruments having full-scale travel as fast as 1 sec and chart speeds up to about 10 in./sec usually used.

Logarithmic amplifier. Used to measure six to eight decades of flux change above about 10^2 n/cm^2/sec; specially constructed to fit application, using a vacuum diode (*10*) in place of fixed input resistor in electronic amplifier, resistance of diode being about 10^{11} ohms at lowest useful current of 10^{-12} amp. May be used either with current chamber or with counting-rate meter from 10^{-12}–10^{-4} amp. Feedback amplifiers also employed in this circuit to obtain input time-constant reduction in the order of 100 times. Output in milliamperes or millivolts displayed on commercial indicating or recording instruments, for which charts, calibrated in as many as 11 decades, can be obtained commercially.

Period meter. Used to measure reactor flux period which bears roughly an inverse proportion to reactivity and affords guide to operator, especially for start up. A useful characteristic is indication of source neutron multiplication upon withdrawal of safety rods with reactor subcritical. Consists of differentiating circuit connected to output of logarithmic amplifier. Output in microamperes, usually 20 μa corresponding to about 1-sec period reading, displayed on commercial microammeter or converted to millivolts to drive commercial recorder. Adjustable-contact relay-type microammeters, used to obtain signal indicating dangerously short reactor periods in the order of 5 sec or less, can set off alarms or trip reactor safety circuits. Output meters operated with zero (∞ period) at center scale to show both positive and negative period values; short period (1 sec) gives positive or negative full-scale deflection.

INSTRUMENT ACCESSORIES

In addition to the basic elements, described under nuclear detectors and indicating instruments, the complete instrument channels require power supplies and cables to complete the circuit. The elements used are commercially available, adapted to reactor instrument use, and rarely peculiar to the nuclear field of application.

Cable. Coaxial-type single-conductor cables, with about 20 $\mu\mu$f/ft, (for example RG-/11U or RG-/59U) used for electric connection between neutron detector and amplifier or current instrument. Multiconductor cables with braided copper shield used where many interconnections between units are necessary. Suitable commercial cables available that have better than 97% braided shield covering and conductor of stranded copper wire in sizes from No. 22 to 18. Coaxial type polyethelene insulated and covered with vinyl. Cables procurable with any desirable combination of materials, for example, aluminum conductors and Nylon covering.

Cable connector. Used to fasten cables to detector and amplifier chassis; commercially available with styramic insulators satisfactory in fluxes up to 10^{10} n/cm^2/sec, encountered at neutron chambers.

Electronic power supplies. Used for B+ supply to electronic amplifiers; available commercially to 500 volts, with better than $\frac{1}{2}\%$ regulation from no load to full load or with line-voltage variation of 20%; ripple less than 0.008 volt, and relatively low internal impedance (10–15 ohms). Also supply up to about 2,500 volts for neutron detectors; have about the same regulation, ripple about 5 mv, and internal impedance about 1,000 ohms.

Dry-cell batteries. Provide reliable, low-impedance source of power for neutron detectors. Several-thousand-volt packages easily assembled from commercially available units, disadvantage being necessity of frequent replacement.

Wet-cell batteries. Standby power source at 115 or 230 volts d-c in various capacities. Typical installation capacity: 400 ampere-hours at 6-hr discharge rate. Commercially available assemblies used, floated on d-c generator driven from a-c power source. This d-c power source frequently used to power d-c motor-driven a-c generator to provide power for vital electronic instruments and control circuits.

Motor-generator set. Both a-c to d-c and d-c to a-c sets used in commercially available sizes to about 10 kw to provide reliable power assembly (see "Wet-cell batteries").

ELECTRICAL PROTECTIVE DEVICES

Reactors are damaged by power operation that exceeds design values. Electrical protective devices prevent this type of damage by initiating rapid negative reactivity changes called "scram" and should be both reliable and fast acting (*1*). These two characteristics usually are not combined in the design of a single unit, so that more than one type of device is used in each protective circuit; several separate circuit assemblies guard against failure of one. False operation of the protective system may be prevented by using a coincidence of two danger signals to initiate protective system operation.

In general, ion current chambers are used to operate these devices, the trip value of current being set experimentally in initial reactor tests to between 110% and 150% of the design power for low-power reactors. Rapid changes in flux are limited to between 3 and 5 sec by period-type protection circuits.

Magnetic relay. Sensitive meter-movement-type relays with an impedance of about 1,000 ohms that close contacts on 20 μa or less available commercially. When made, contacts held closed by permanent magnets until reset. Relays connected directly in ion current chamber circuits to operate at fixed chamber current corresponding to about 110% to 150% of reactor design power. Current set by adjustable shunting of relay or by moving chamber to location where high flux will produce required relay trip current.

Electronically operated relay. Used to detect current corresponding to about 110% to 150% of design power in an ion current chamber circuit. Consists of a combination of an electronic amplifier designed to operate commercially available sensitive relays that pick up at about 1 ma and fall out at about 0.5 ma. Circuit arranged to cause relay to fall out when producing scram action, providing fail-safe type signal against loss of power supply.

Period meter. Used to initiate protective action when

period of 3 to 5 sec (*1*) is detected by period meter (described under "Indicating Instruments"). Trip action initiated by: commercial meter-movement-type relay requiring about 20 μa to close contacts; electronically operated relay attached to period circuit; or by standard cam-operated contacts installed in commercially available 0–10 or 0–50 mv recorders.

AUXILIARY INSTRUMENTATION

Auxiliary equipment such as blowers, pumps, and heat exchanger are essential to safe and proper reactor operation. Measurements of quantities such as pressure, flow and temperature are made and displayed in the control room. Similar measurements are made for the prime purpose of setting off alarms or initiating fast negative reactivity changes in the reactor.

Selection of the components of this system depends upon plant design, and the devices used are not peculiar to nuclear applications. Suppliers of commercial instruments for general industrial use either have standard units to fill requirements, or can adapt their standard units to the special plant needs.

Flow meter. For liquid coolants, such as heavy or light water, flow usually measured with orifice-type or Venturi-type flow meters that operate on differential pressure principle, or magnetic flow meters that are essentially electric generators. Commercially available assemblies calibrated by manufacturer for temperatures from 20° C to several hundred degrees as required, with nominal accuracy of 1% of operating range specified. For liquid metals magnetic flow meter used, essentially a d-c generator (*13*) that normally has output of 0–5 mv, usually recorded on a commercial millivolt recorder. Commercial instruments can be equipped with electric contacts for signal or protective-circuit operation.

Pressure gage. Gas such as helium having properties suitable for use in reactors may be employed to provide atmosphere for reactor or some portions of reactor. Gas pressure ranges from fraction of pound to several pounds. Information about pressure at various locations around reactor indicated by commercial gages; electric contact-making gages useful to operate alarms. Remote indicators of several commercial telemetering types used to transmit pressure information to operating and control room. In addition, wide range of commercial gages used generally to indicate and record pressures in plant auxiliaries.

Temperature instruments. Used extensively to indicate such quantities as reactor coolant temperature, air temperature both at reactor and outdoors, and heat-exchanger coolant temperature. Primary sensing elements for most applications can be recommended by manufacturers. For air temperatures up to 150° C commercial mercury or gas bulb-type instruments with accuracy of $\frac{1}{2}$% of range generally used, with indicator operated directly from capillary tube running between instrument and measuring location. Temperatures above about 150° C usually measured by commercially available resistance thermometers or thermocouples, protected by stainless-steel housings to provide easy replacement, mechanical strength, and to prevent deterioration.

BTU meter. Used to measure absolute value of reactor power as indicated by temperature and flow of coolant. Commercially available units designed and calibrated to measure in a specified power range with nominal 1% accuracy. Value indicated by this meter used to calibrate nuclear instruments in average reactor power when reactor power has been held constant for several minutes. (The neutron detectors used for control read only a relative value of flux at point outside reactor proper but follow rapid flux changes.)

FLUX-CONTROL SIGNAL AMPLIFIERS

Reactor flux is usually controlled by mechanically changing reactivity (*1, 2*) through remotely operated rods (see "Reactivity Control"). The signal to change rod position is initiated at the control board by the operator or by a feedback control system for automatic flux regulation. The current magnitude used for a control signal is about 10^{-6} to 10^{-4} amp with a 10^7 to 10^8 ohm source impedance; it must be converted to several watts at a low impedance suitable for driving the next unit in the control loop—a rotating amplifier, hydraulic amplifier, or relay. The design and application of these amplifiers are determined by feedback control system considerations.

D-c amplifier. Used to amplify ion chamber current signal; specially designed to fit application. Amplifier input circuit provided with built-in bucking current or voltage source to provide control point or power reference value. Total input resistance of amplifier 5×10^6 ohm or more. Resistance changed logarithmically with respect to displacement, so that constant-speed motor drive can be used to change power reference setting or control point at constant flux periods of 20–40 sec. Input circuit sometimes designed to provide constant gain in per cent of demand value over 10^2 range so that control accuracy better than $\pm \frac{1}{2}$% of demand power can be maintained over this range.

Micromicroammeter, recorder. Used to convert ion chamber current signal into millivolt signal to drive recorder; both units commercially available. Output of pair results in mechanical displacement proportional to current input signal, can be adapted (*1*) to drive power amplifier of flux control loop. This type amplifier useful for control over five or more decades of reactor flux.

Vibrating-reed electrometer. Used to convert ion chamber current into mechanical displacement; adaptable to flux regulation in a manner similar to $\mu\mu$ammeter.

POWER AMPLIFIERS

Motors in the sizes from $\frac{1}{10}$–5 hp are used to drive the reactivity controlling rods, and therefore power amplifiers are needed to start, stop, and change speed of these motors. Automatically controlled rods associated with the flux regulating system either are driven at preset values of speed or are torque controlled through the proportioning action of the control signal amplifier (*1*), which may have a power output of 1–10 watts. Power amplifiers furnish power gains of 10–5,000 in normal reactor-control service.

Motor starters. Used to operate d-c and a-c motors from source of fixed or variable voltage as required by application. For automatic control of reactor power they operate regulating-rod drive motor in "on-off" or discontinuous type systems, where rod speed is fixed at a predetermined optimum value and is not made proportional to error between flux demand and reactor flux signal, as is case for proportional-type feedback control systems. Commercially-available reversing type, sized to match motor load, provide both positive or negative reactivity control changes. Usually a set of three normally-open contacts required; for d-c motors at least one set of normally-closed contacts required for dynamic braking.

Rotating amplifier. Commercially available power amplifiers, essentially a-c induction-motor-driven, d-c generators, used to control speed of d-c motors ranging from $\frac{1}{10}$ to about 5 hp that drive shim and regulating rods. Signal controlling rotating amplifier may be obtained from manually-operated current or voltage source—battery and potentiometer or autotransformer and rectifier rated at 1–10 watts—or may be controlled by flux signal amplifier for automatic flux regulation.

Hydraulic amplifier. Used to convert control-amplifier electric signal or operator-controlled signal, at power level of 1–10 watts, to hydraulic power signal suitable for controlling hydraulic motors or pistons. Essentially magnetically operated valves, specially designed and furnished by manufacturer of hydraulic equipment used with hydraulic piston or motor drive unit.

REACTIVITY CONTROL

The reactivity of most nuclear reactors is controlled by rods which, in thermal reactors, have their greatest effect by absorbing neutrons, or, in higher energy neutron reactors, change the reactor leakage, by moving reflector or moderator, or change the loading of the core by moving the fuel (*11*). Rod design and selection of materials is fixed by the reactor design. Absorbers such as cadmium and boron are used and are often clad in steel or aluminum to provide mechanical rigidity and protection. The designation "control rods" is generally given to any mechanical device which functions to change reactivity, although some units may be quite massive.

In some cases emergency reactor flux control is achieved by allowing boron steel shot, or similar neutron absorbers, to spill into tubes placed in the reactor for that purpose.

Safety rods. Used to provide several per cent of negative reactivity, under all possible loading and ambient conditions contemplated for reactor, with all other rods in their maximum positive reactivity position. Rods and associated drives designed to change reactivity in positive direction at about 0.1%/sec, and to be moved through their entire stroke before shim rods are moved (reactor still suberitical). Usually magnetically latched in ready position for scram action (fast reactivity reduction) under forces developed by gravity, springs, flywheels or hydraulic pressure accumulators. Compact rods usually raised by motor-driven cable hoists, commercially available, with clutches designed to release rod for scram action. More cumbersome assemblies lifted by specially designed hydraulic pistons or screw jacks. Shock absorbers used to stop scrammed rods, prevent damage to rod and structural supports.

Shim rods. Used to provide reactivity control in amount dependent upon reactor purpose and operating conditions (see for example Ref. *1*, "Excess Reactivity Requirement"). Shim-rod drives designed to move rods slowly in both positive and negative reactivity changing directions at speeds of from 0.01% to 0.1%/sec (usually adjustable over that range). Ball-bearing screw jacks or rack and pinion drives used; designed to position the rods to about 0.001% reactivity change, corresponding to mechanical movement of 0.01 to 0.04 in. Backlash which may result in any tendency for small uncontrolled movements under coolant-developed forces and gravity must be avoided, because it contributes to reactor noise and instability. Individual rod weights generally held between 15 and 150 lb, several rods being used in reactor (*11*).

Regulating rod. Used for fine reactivity control, changes in the order of 0.001% at maximum speeds which range from 0.001%/sec to 0.1%/sec; usually driven by servo-type two-phase a-c motors or d-c motors, to obtain means of speed adjustment that provides flux- or power-regulating system gain control. Maximum reactivity controlled by this rod held to total of 0.6% or less depending upon ability of safety system to prevent dangerous reactor flux changes. Drive mechanisms either ball-bearing screw jacks, or rack and pinion. Rod weight held to 10–50 lb to reduce control power requirements.

Shim-safety rods. Used in many reactors to combine safety-rod and shim-rod action; ball-bearing screw jacks or rack and pinion drives move rods slowly in positive or negative reactivity changing direction. Holding magnets, magnetic latches, or clutches release rod, from any operating position, for movement in negative reactivity changing direction under power from sources of stored energy such as springs, gravity, or hydraulic accumulator pressure. Speed range used for control at normal power operation is about 0.001% to 0.01%/sec, is adjustable in that range. Scram speed as high as possible, with shock absorbers arranged to stop the rods at end of stroke.

ROD DRIVE COMPONENTS

Mechanical assemblies, for moving the reactivity control rods, are made up of commercially available units. Rods may be moved horizontally, vertically, or swung through an arc. Basically, the choice of design components hinges upon a means of converting rotational to linear motion and the selection of a motor type and speed. Special bearings are required for service inside reactor shield, since lubricants deteriorate rapidly in neutron flux and the bearings are relatively inaccessible for maintenance.

D-c motors. Used to drive all types of control rods and associated rod-driving-mechanisms. Commercially available types in sizes from $\frac{1}{20}$–3 hp used. Starting time constant usually 30–100 msec. Reliable operation obtainable over adjustable speed range of 10–1. Voltages 12–230 volts; usually supplied by full-wave rectifiers and autotransformers connected to a-c supply line. Motor armature impedance 100 ohms or less. Motor fields operated constantly excited to obtain dynamic-type braking action for accurate rod positioning.

A-c motors. Single- and three-phase 60-cycle, commercially available; used to drive shim, safety, and shim-safety rods at selected constant speed. Use variable-ratio gear transmission that provide adjustment, continuously or in steps, over a range of 10 or more in speed. Advantage is fixed maximum speed set by line frequency. Motor sizes used range from $\frac{1}{4}$ to 5 hp. Commercially available two-phase, servo-type motors, at line frequencies of 60–400 cycles/sec used to drive regulating rod. Speed and torque varied by autotransformers for manual adjustment, or by amplifiers controlled by flux signals from ion chamber (*1*).

Hydraulic motors. Used to drive all types of control rods in applications where unit can be mounted a few feet outside reactor shield to avoid rapid oil deterioration due to effect of neutron flux. Sizes from $\frac{1}{2}$ to 5 hp used; available commercially as unit including pump and electrically-controlled valves suitable for speed adjustment over a range of 20 or more, the wide speed range being a feature of this type of assembly.

Lead screw and nut. Used to drive all types of control rods. Type having circulating-ball type nut (ball-bearing

screw jacks) preferred for its relatively high operating efficiency as compared to acme screw and nut type. Units commercially available with screw leads of $\frac{1}{8}$ to $\frac{1}{2}$ in. Usually made to order for drive application.

Rack and pinion. Used to drive all types of control rods; provides accurate positioning. Commercially fabricated out of steel or other suitable metals to meet specifications of particular drive application; usually guided with roller and ball types of bearings.

Cable hoists. Used to move vertically-operated safety rods weighing up to about 100 lb. Drum-type cable hoists available commercially, consist of suitably sized a-c induction motors, gear heads and limit switches.

Holding magnets. Used on shim-safety and safety-rod drives to provide for scram-action release of rod from drive mechanism (*1*). Units specially designed, usually clad with stainless steel for protection of magnetic material and lead wires; holding force usually about 150 lb. Mating faces on rod and drive members designed for quick release; zero-current holding force as low as possible, fast release expedited by providing about a 0.002-in. gap clearance in the face (*12*). Magnet supply power is d-c. Magnet wire usually covered with good grade of glass insulation.

Magnetic clutch. Commercially available friction-type magnetic clutches used to separate section of drive shafting in safety or shim-safety rod drive system. Design such that clutches deenergized for scram, drive motor and gear head being released, and stored energy from a spring or gravity being allowed to drive rod in scram direction.

Springs. Specially designed steel springs used as energy storage units to provide scram action on safety or shim-safety rods. Tailored to each application; forces developed usually sufficient to produce acceleration of 2–10 g.

Shock absorber. Used to stop scrammed control rods. Specially designed; usually use air or oil where stopping action is applied to rod drive mechanism, or use reactor coolant as compressive medium where rod itself is released from drive. Commercial units available with variety of force vs distance characteristics suitable for stopping rods weighing 20–100 lb at speeds of 10–20 ft/sec. To insure sufficient fast rod travel shock absorber action usually limited to about 10% of rod stroke.

Limit switch. Limit switches of precision snap-action type, rated at about 5–15 amp a-c and $\frac{1}{4}$–$\frac{3}{4}$ amp d-c at 110 volts used extensively as: travel limit devices, position indicators, positional interlocks, control switches. Compact and reliable commercial units available.

Position indicators. Control-rod positions indicated remotely by instrument-type synchro pairs having restoring torque of about 0.5 oz-in. for 10-degree displacement. Units used to drive light-weight balanced needles with clock-type dials, calibrated in suitable units of displacement. Necessary to gear driving unit down with accurate gear trains to obtain remote indications of displacement corresponding to about 0.0005% reactivity change. For measurement of smaller displacements two synchro pairs used, one coarse, one fine, incorporated as part of an instrument servo that inherently eliminates any possibility of an incorrect reading and permits driving auxiliary control devices.

Tachometer. Used to stabilize regulating-rod feedback control systems (*1*) and to operate specially designed overspeed and overtravel units to prevent improper flux regulation or control-system failures. Generates voltage proportional to speed; typical commercial units rated at about 1 volt/100 rpm, with load impedance 10,000–100,000 ohms.

OPERATIONAL DEVICES

The operator is provided with a control console from which he can change the position of rods, switch into automatic control, and scram the reactor. An intercommunication station is usually provided for contacting other locations around the reactor. Displayed conveniently on the console are: an instrument for reading ion chamber current and, for accurate control of power, a meter indicating differential current (difference between desired and actual ion chamber current); shim- and regulating-rod position indicators; and pilot lights showing the position of safety rods and the condition of safety or protective circuits. All other instruments associated with the reactor equipment are usually arranged in convenient locations on additional panels easily seen by the operator but not necessarily close at hand.

Selector switch. Used to prevent simultaneous operation of rods or specified rod groups to avoid changing reactivity at too high a rate. Usually inserted in control circuit between rod drive motor or motors and control relays or contactors. Made to order commercially, using standard contact assemblies rated at 5–15 amp, 110 volts, with banks of 3 to 6 sets of contacts, functioning simultaneously, to operate indicator lights, relays, and for interlocking purposes.

Push buttons. Momentary-contact types used to operate electric motors, starters, magnetic valves, scram circuits, relays, similar devices. Commercially available with two sets of both normally open and normally closed contacts, in ratings up to 15 amp, 110 volts.

Relays. D-c or a-c type, rated 5–15 amp, 110 volts, requiring up to 1 amp to operate, used extensively in sequence interlocking control and annunciator operation. Usually at least two normally open and two normally closed sets of contacts; commercially available with four or more sets of each type of contact.

Annunciator. Specially constructed, or a commercial type adapted to sound an alarm and indicate dangerous conditions such as: high flux, short flux period, high temperatures, loss of or excess pressures, failure of power supply, malfunction of control sequences, improper operations. Some indications also used to scram reactor. At least 10 such indicators usually required; total number varies widely.

* * *

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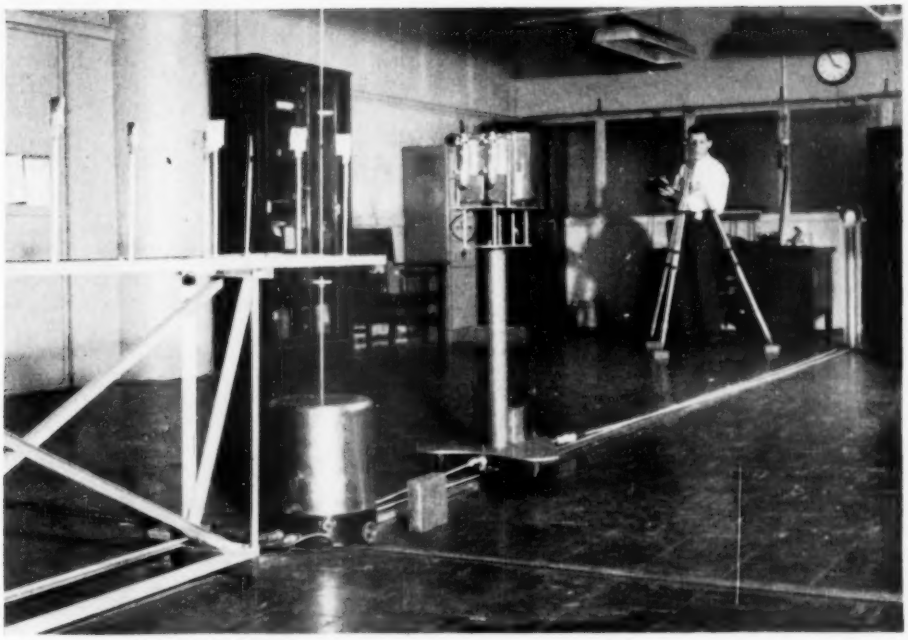

CALIBRATION ROOM for reactor installation is similar to this one at AEC's New York Operations Office. Note jig for holding film badges, instruments on remote-control dolly, next to source shield

Radiation Safety for a Reactor

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THE BASIC REQUIREMENT of adequate radiation safety for a nuclear reactor significantly affects virtually every consideration in the design, construction, operation and maintenance of such a facility. A brief summary of the scope and problems of a reactor radiation protection program may be of assistance in appreciating the types of materials and equipment required.

The fundamental problems of radiation protection exist for all types of reactors. There is the basic problem of the primary shielding of the critical assembly, and the equally important problem of protection from any material which has been exposed to the neutron flux of the chain reaction, as almost all substances become radioactive under neutron bombardment.

Techniques of protection must consider the two general types of radiation hazards: the control of "radiation" from a remote or enclosed source, and the control of "contamination"—radioactive material, usually finely divided such as dust or moisture, that has escaped from the principal source material, and has deposited on surfaces or become suspended in air. The hazard of pure "radiation" sources is one of external exposure which must be limited in accordance with prescribed permissible limits, usually on a weekly basis. Radiation exposure from "contamination" sources presents a more difficult control problem as such sources also produce internal exposure in that the radioactive material may enter the body through inhalation, ingestion, absorption through the skin, or entry through a break in the skin.

DESIGN CONSIDERATIONS

Plans for a reactor installation should include consideration on a radiation protection basis of the facility arrangement, the construction materials, and the use of permanently installed monitoring systems.

Facility Arrangement

The provision of adequate reactor radiation protection starts with the preliminary scope design of the facility arrangement. If the reactor, operating zones used for introducing into and removing materials from the reactor, areas for repair and storage of materials removed, and exhaust-air handling facilities are grouped effectively and

INSTRUMENT REPAIR and maintenance is necessary for proper operation of a health-physics program

PROTECTIVE CLOTHING is worn in radiation zones when required, varies with hazard

segregated from the areas normally occupied by personnel during routine reactor operation, the possibility of effective radiation protection and control is greatly enhanced. When personnel access to the "radiation zone" portion of the facility is restricted to one or two easily controllable routes, contamination control is made practical. Provision of proper equipment at such access points for survey of personnel, clothing and equipment, plus facilities for decontamination of material to be removed from the radiation zone, is essential.

Arrangement of the reactor building ventilation system normally provides for flow of air from zones of least expected contamination, to reactor radiation zones and then to exhaust stack. Ventilation system controls should provide for continuity of air flow.

Materials of Construction

Consideration must be given to materials used where removal from the reactor is planned or maintenance is required. Examples of such equipment are reactor control mechanisms and exposure assemblies for isotope production. In general it is desirable to use materials which do not become intensely radioactive, or if this is unavoidable, to use materials with rapid decay rates, so that shielding required to control radiation hazards following equipment removal may be minimized. To reduce contamination problems, assemblies exposed to neutrons should have surfaces which will not produce corrosion products that can spread as a dust onto surfaces and into the air.

Reactor building surfaces which may be subject to contamination must be considered with respect to ease of cleaning. Most contaminants encountered from induced activities of reactor equipment are fortunately not as corrosive to surfaces as those encountered in a radiochemical laboratory. Smooth concrete and steel surfaces protected with plastic-base paints are normally satisfactory. In particular cases where chemical attack is a potential, design requirements are similar to those appropriate for radiochemical laboratories.

Installed Monitoring Systems

Permanent systems can be planned and used for area monitoring, air monitoring, and water coolant monitoring. The gamma monitoring system discussed here can in some instances appropriately include neutron-sensitive chambers.

Gamma monitoring system. It is usually considered appropriate to establish a system of installed monitoring instruments in the various radiation zones around the reactor with the indicated dosage rates continuously recorded at a central point, preferably at the personnel access locations. Thus the general radiation levels of interest are immediately available prior to entry of personnel into the radiation zone areas. Significant changes in the radiation hazards picture are promptly detected, and correlation with operating conditions will allow determination of causes. Careful consideration as to proper placement of the monitoring chambers must be made to provide a maximum of information.

Such a system provides useful general information but may not be indicative of localized radiation conditions and hazards, which are best determined by surveys with portable monitoring instruments when general changes are apparent from the recording instruments.

To assist in the immediate detection and investigation of

significant changes indicated by an installed monitoring system, it is often appropriate to place alarm trips on the recorders, with the alarm settings at a point say 50% above the expected radiation level. Economy in such a system is possible by the use of multiple-point switches, amplifiers and recorders to service a number of monitoring chambers. This is generally safe as such commercially available equipment has a time cycle of only several minutes.

Air monitoring system. The determination of concentration of radioactive material in the air in the radiation zones around a reactor is greatly facilitated by the use of an installed air sampling system. A piping system actuated by a central vacuum pump is appropriate when it is planned to operate the reactor over a period of years. The maintenance of such a system is usually only a fraction of the cost of maintaining an equivalent group of portable air sampling machines.

Such a system is equally usable for filtration sampling for dusts and aerosols, for determining the presence of radioactive gases in the air by drawing the air sample through an appropriate ionization chamber, and for air sampling by scrubber techniques for radioisotopes not readily detected by filtration or direct measurement. Such installed equipment is particularly necessary for the continuous monitoring of reactor-area ventilation air to be discharged to atmosphere, and for reactor coolant air in the case of an air-cooled reactor.

Water coolant monitoring. In reactors where water is used as either the primary or secondary coolant, it is usually necessary to discharge the water to a public stream. Thus the reactor operator has a significant responsibility to the public to insure that the effluent is safe with respect to content of radioactive material.

Where water is the secondary coolant, with the primary coolant being a recirculating system, the problem is simply the determination of whether any of the primary coolant has escaped into the secondary coolant stream. Thus control is possible by ionization chambers immersed in the effluent water stream, and by continuous water sample evaporation and measurement techniques, each with suitable recording and alarm instrumentation.

Where water is the primary reactor coolant, as at the Hanford piles, induced activities are present in the coolant because trace quantities of soluble salts are subjected to neutron bombardment as the water passes through the reactor. Retention of the effluent in large basins for several hours is necessary to allow decay of the short-lived isotopes before the water is returned to the Columbia River. When returned to the river, about 95% of the activity is still due to short-lived isotopes, but trace quantities of isotopes of phosphorus, iron, and calcium are present. Thus careful monitoring of the effluent activity, knowledge of the radiochemical composition of the released water, and measurement of minimum dilution assurable in the river is necessary.

The provision of adequate instrumentation is complicated by the fact that monitoring equipment in contact with the water tends to become contaminated, and undesirable background buildup occurs. Therefore, measurements must be made with equipment which does not contact the water. Continuous external measurement of gamma radiation from the large water mass in retention basins is a practical method of indicating changes in effluent activity, but must be backed up with frequent sampling for determination of activity density and radiochemical composition. Several systems of continuous sampling are under development.

OPERATING CONSIDERATIONS

Maintenance of adequate radiation protection requires a continuing, active program, adequately staffed. Included in this program should be personnel metering, radiation zone control, radiation measurements, and instrument calibration.

Monitoring Organization

It is usually desirable to provide personnel for radiation monitoring work who do not have other responsibilities. Some 3 to 5% of the total operating personnel may be needed to carry out a radiation protection program.

Personnel Metering Program

A permanent record of radiation exposure of all reactor operating personnel is essential for adequate radiation control. In addition to providing information for annual and lifetime exposures, daily use of personnel metering instruments provides early warning of significant exposures, either planned or unplanned, so that additional radiation work may be regulated by supervision as necessary.

Film badges and pocket chambers should be worn within the reactor operating area, whether radiation zones are entered or not. Tamperproof film badge construction is desirable.

Radiation Zone Control

Radiation hazards control is dependent on some form of supervisory management of entrance to, work within, and exit from radiation zones. Standard operating procedures are appropriate for routine work, and temporary control procedures are suitable for nonroutine operations. Facilities and equipment that assist in proper radiation and contamination control are listed in the section on zone control on page 45.

Radiation Measurement Laboratory

In the operation of a reactor radiation protection program, a radiation measurement laboratory is essential for routine counting and analysis of samples. Air-sample filters must be counted. Air-sample scrubber solutions must be prepared for analysis. Routine effluent coolant-water samples require radiochemical analysis.

The gaseous and liquid effluents from the reactor may require routine environs monitoring which will produce samples of soil, vegetation, and public waters. These samples require evaluation with regard to radioactive content to insure that the reactor operation is not adversely affecting the public domain.

Instrument Calibration Laboratory

As a radiation protection program can be no better than the instruments used in making the radiation and contamination surveys, the importance of accurately calibrated measuring instruments in good repair is evident. A facility is required in a low-background area where recalibration and repair of all instruments can be done on a routine basis.

Radiation sources are required for alpha, beta, gamma, slow-neutron, and fast-neutron calibrations. Source strengths must be appropriate for the most sensitive detection instruments, and for calibration of high-range dosage measuring instruments. Survey and decontamination equipment is required to insure that the instrument itself is free of contamination prior to recalibration. Personnel

meter films from the film batch in service in the reactor area must be exposed to known quantities of radiation, so that quantitative evaluation of actual film darkening may be made.

Such a facility requires a small-scale radiation protection program of its own, to insure that the calibrators are properly protected in their work with radiation sources. This protection is afforded by semi-remote manipulation of the sources and instruments, and by the use of visual aids such as telescopes so that the calibrator can always remain at a safe distance from the source.

EQUIPMENT TABULATION

The preceding summary of factors involved in a radiation protection program for a nuclear reactor gives some indication of the diversity of materials and equipment required. Tabulated here are some of the more significant components, most of which are in use at Hanford. Items are commercially available, except those marked (*) which indicates parts commercially available with assembly and arrangement for local conditions, and those marked (†) which are specially designed for particular problems.

Monitoring Instruments, General Survey

Alpha detection. Poppy, both portable and power-operated types in use. Probe size usually 2 × 7 in. Sensitivity as low as 500 dpm generally obtainable. Used for detection-type survey of personnel, clothing, protective equipment, surfaces, tools, etc.

Alpha measurement. Three types of instruments are in general use:

Poppy. Semiquantitative up to about 40,000 dpm.

Alpha meter (Zeuto). Two ranges, useful in range of 200 to 50,000 dpm.

Juno. Three ranges, useful for measurements of 4,000 to 5,000,000 dpm.

Beta-gamma detection. Three useful detectors are listed:

Portable G-M meter. Three ranges, sensitivity of 100 to 80,000 cpm. Useful for detection-type survey of personnel, clothing, protective equipment, surfaces, tools, etc.

*Scaler with G-M probe.** Useful at monitoring stations at exit from radiation zones. Utility increased for semi-quantitative surveys when arranged with audible signal for every eighth count.

X-ray film packets. Particularly useful in determining location, size, and approximate dosage rate from beams at reactor experimental holes, etc.

Beta-gamma measurement. Quantitation of one or both types of radiation can be accomplished with the four instruments listed.

CP meter. Three ranges, useful for gamma measurements in range of 5 mr/hr to 5 r/hr. With thin end-window chamber for beta surface dosage measurement from about 15 mrep/hr to 35 rep/hr.

Juno. Three ranges, approximately same utility as CP. May be energy dependent.

TP meter.† Adaptation of CP meter for high-range beta-gamma survey with extension probe. Two types of instruments with maximum ranges of 5 and 500 rep/hr.

Beckman. Four ranges up to 2 r/hr. Very reliable for pure gamma radiation only. Not useful when beta radiation is present.

Slow-neutron measurement. A BF_3 counter is useful in range of 0.1 to 25 mrem/hr, is qualitative for fast neutrons. Slow-neutron pocket ionization chambers used for dosage rate measurement of small radiation beams from reactor.

Fast-neutron measurement. Neut† provides differentiation of gamma and fast-neutron radiation by alternate use of argon- and methane-filled ionization chambers. Sensitivity for fast neutrons from 10 mrem/hr to 17 rem/hr.

Monitoring Equipment, Installed Systems

Reactor radiation zone. Typical components of a beta-gamma monitoring system are:

Plastic gamma-sensitive ionization chambers. With thin plastic beta-sensitive window. Gamma sensitivity approximately 4×10^{-13} amperes for 1 mr/hr.

Multiple switch. For cyclic monitoring from a group of ionization chambers.

Amplifier. For indicating chamber ionization currents.

Multiple-point recorder. Provides time record of dosage rates indicated by system.

Alarm. For significant change in radiation level.

Vacuum air-sampling system. Principal components of this system are:

1. Vacuum pump with regulation for constant receiver vacuum.

2. Piping distribution system† to points requiring air sampling (radiation zones, exhaust ductwork, stack).

3. For dust sampling, filter-paper holders with control valving and air-flow indicating gages.*

4. For radioactive gas sampling, air drawn through ionization chamber† for direct measurement, with ionization current fed to amplifier and recorder. Alarm connection appropriate.

5. For particular isotope sampling, air drawn through appropriate scrubber solution apparatus, with air-flow valving and gages.*

6. Alternate air moving equipment. Where installed vacuum system is not justified or where occasional sample is required at location not covered by piped system, semi-portable electrically operated vacuum pumps used.

Reactor water coolant monitoring. If water is the primary or secondary reactor coolant, it must be monitored. Instrumentation is required for checking effluent activities and flow rates.

Secondary coolant. Where normally uncontaminated, use immersed thin-wall stainless-steel G-M tube, with counting-rate meter, recorder, and alarm.

Primary coolant. 1. Control by gamma-sensitive chambers suspended over large mass of effluent water; instrumentation as for radiation zone installed monitoring system.* 2. Sampling points for periodic removal of water sample, for evaporation, counting, radiochemical analysis.

Effluent monitoring.† For continuous monitoring of water coolant discharged to public waterway, automatic equipment provides for continuous or frequent sample removal to sample conveyor, evaporation of water sample, counting of residue with recording and alarm, and disposal of sample-conveying medium.†

Effluent flow rate. Usually available on reactor coolant supply instrumentation; need not be duplicated.

*Public waterway flow rate.** Instrumentation to provide knowledge of dilution as effluent is released. Water stage recorder at a calibrated channel cross-section. Not required if information available from upstream dam, etc.

General personnel monitoring. Five-fold hand and shoe counter for detection of beta-gamma contamination; four-fold hand counter for detection of alpha contamination.

Personnel Metering Equipment

Film badge.* With shield, for beta-gamma exposure, containing sensitive and insensitive film packet developed each week.

Pocket gamma chambers. Approximately 300 mr full scale, worn in pairs, read at end of each work day.

Pocket slow-neutron chambers. Approximately 200 mrem full scale, worn in pairs, read at end of each work day. Normally worn only when entering reactor radiation zones when reactor is operating.

Fast-neutron film badge.* Contains alpha emulsion film, developed each week; normally worn only when entering reactor radiation zones when reactor is operating.

Finger rings.* Contain beta-gamma sensitive film, worn when working on jobs where hand exposure is significantly greater than full-body exposure.

Electrometer. For charging and reading gamma and slow-neutron pocket chambers.

X-ray unit. For identifying film packets before removal from badge.

Riveting and deriveting machines.† For changing film-badge packets.

Darkroom facilities. For developing film packets.

Densitometer.* For metering degree of darkening of developed beta-gamma films.

Microscope. With accessories for counting alpha tracks on fast-neutron monitoring film.

File room. Facilities for permanent exposure records of all personnel.

Radiation-Zone Control Equipment

Radiation zone signs. Posted for delineation of controlled areas.

Operating procedures. Standard or temporary, prescribing radiation protection techniques to be observed.

Clean protective clothing. To be used in degree appropriate for hazards anticipated and work to be done.

Shoe protection. Canvas shoe covers, rubber footwear.

Body protection. Laboratory coats, coveralls, rubber or plastic suits, cloth or plastic hoods for head and neck.

Hand protection. Rubber, surgical rubber, cotton, plastic-coated cotton, or leather gloves.

Respiratory, face protection. Respirators, full-face masks with high-efficiency filters, oxygen or fresh-air masks for radioactive gas atmosphere.

On-the-job equipment. For radiation and contamination surveys, setting of time limits, control of radiation hazards.

Monitoring instruments. See preceding listing.

Clocks. For timekeeping; stopwatches used when time limits are less than say 10 minutes.

Handling equipment.† For semi-remote handling of radioactive equipment.

*Temporary shielding.** For specific jobs.

Contamination control station. Located at exit from radiation zone. Equipment includes:

Detection-type instruments. Previously listed, for surveys of protective clothing prior to removal, radiation monitoring instruments, exposed skin and personal clothing, and tools and equipment used in work.

Laundry hampers. To receive used clothing.

*Skin decontamination facility.** Includes sink, work bench with survey instruments; decontamination equipment—approved soaps and chemicals, medical applicators and swabs, contaminated waste cartons; shower stall for emergency treatment for severe general-body contamination.

Equipment decontamination facility.† Includes contaminated tool and equipment storage space, hooded work bench with sinks, decontaminating agents and implements, equipment drying space, survey instruments, and contaminated waste containers.

*Mask cleaning facility.** For sanitary cleaning prior to reissue of uncontaminated masks. Masks found contaminated to go to equipment decontamination facility first.

Environs Monitoring Equipment

Air monitoring.* Stack effluents monitored with equipment listed under "vacuum air-sampling system" items 3–6, at selected sites considering prevailing winds, etc. Precipitation collection apparatus usually at same locations.

Terrain monitoring. Elementary equipment for sampling surface soil and vegetation.

Public-waterway monitoring.* Required when reactor coolant is released thereto. Sampling boat equipped with: water sampling pump for surface and subsurface samples; small dredge for bottom sampling; fishing tackle, nets, and plankton filters for collection of aquatic life.

Radiation Measurements Laboratory

General requirements. Radiochemical laboratory requirements are given in "Guide for Selection of Equipment for Radioactivity Laboratories" (NUCLEONICS **7**, No. 5, pgs. R-3 to R-11, 1950).

Instrumentation. Detectors and accessories are required for alpha, beta, and gamma radiation, including:

G-M tubes. Thin end-window, lead shielded, used with scaler. Used for determining beta counting rate of samples from radiation-zone monitoring, and effluent-water and environs monitoring program.

Horizontal shielded G-M counter. For determining beta counting rate of air-sample filters.

Alpha counter. With "standard" and "long tom" chambers for determining alpha counting rates of samples when required.

Instrument Calibration Equipment

Laboratory area. Adequate room needed for source and instrument manipulation and to minimize backscatter from building walls by distance.

Radiation sources. Fissionable material and some sources are controlled by AEC. Sources include:

Radium or cobalt-60. Range of 0.1 mg to 0.5 gm Ra for gamma calibration of all types of instruments.

X-ray machine. For gamma calibration at lower energies.

Uranium metal. For surface beta dosage rate calibration.

Alpha emitters. Plutonium, other alpha emitters, in trace quantities, properly mounted, for alpha instrument calibration.

Fast-neutron sources. Ra-Be, etc., for calibration.

*Moderators.** Graphite or paraffin for use with fast-neutron sources for slow-neutron calibration.

Auxiliary equipment. Includes handling and protective equipment, such as:

Jigs.† For mounting instruments at prescribed distances from source.

Trolleys.† For moving instruments to various distances from source.

Handling equipment.† Semi-remote equipment so that calibrator may remain at safe distance from source.

Telescopes. For reading instruments at safe distances.

Use of a Reactor for Research

By MARVIN FOX

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NUCLEAR REACTORS PRODUCE essentially a single, primary product—neutrons. A large and varied program of experimental usage can be supported simultaneously by a single reactor, in spite of the fact that the neutrons perform services of widely different character. This section will attempt to outline the many different kinds of typical research problems that depend upon reactor neutrons as their fundamental requirement, and the facilities, special equipment, and gadgetry necessary to the conduct of the experiments and the associated operational effort.

SOME DESIGN CRITERIA

The neutrons from a reactor extend over a considerable energy spectrum.* Almost every application of neutrons has, to some degree, a limited range of neutron energies effective in producing the results sought. In some cases, it matters very little that the energy range of the available neutrons is much wider than is required, so that there is no necessity for limiting the spectrum. An example of this is the ordinary production of radioisotopes by irradiating target materials to induce the thermal-neutron (n,γ) reaction. The more energetic neutrons contribute almost nothing to this reaction, and their presence during the irradiation is ignored.

In other cases, it may be very important to select, from the wide spectrum, a limited band of energies by some device which eliminates or converts the extraneous neutrons. An example of this is the thermal column that serves to provide a spectrum rich in slow neutrons. Another example of this, but in the opposite direction, is a device, commonly referred to as a "doughnut," that provides a fission spectrum of neutrons. This device is simply a cavity enclosed by walls of uranium which are black to slow neutrons. The slow neutrons are absorbed in the walls to cause fissions in the U^{235} and yield only fission neutrons in the cavity.

In still other cases, it is necessary, in addition to limiting the neutron spectrum, to modify or reduce the gamma-ray spectrum which is a large part of the reactor radiation field. This is usually accomplished by a layer of bismuth.

* D. J. Hughes, NUCLEONICS, **11**, No. 1 (1953).

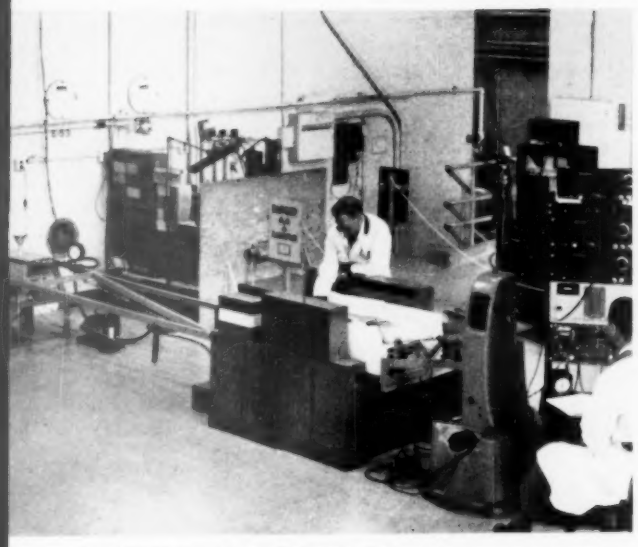
In addition to the large decisions on type of reactor, operating power level, and neutron flux, several other considerations are important in the design of all research reactor facilities.

Shielding. The first essential is a good shield to suppress the leakage radiation to a point consistent with the background contributed by the research work itself. However tight the restrictions on the experimental activity are made, there is always some background contribution due to the neutron beams or active materials in use. For a reactor supporting a large program of research, such as the one at Brookhaven, a reasonable design value for the shield penetration is 0.5 mr/hr. This rate is equivalent to 150 gammas/cm²/sec of 2 Mev energy, or to 100 thermal neutrons/cm²/sec, or to 10 neutrons/cm²/sec of 2 Mev energy, or 6 betas/cm²/sec of 1 Mev energy. It is somewhat less important to construct the shield of materials that achieve this background penetration in a minimum thickness, with due regard to the economies of the situation.

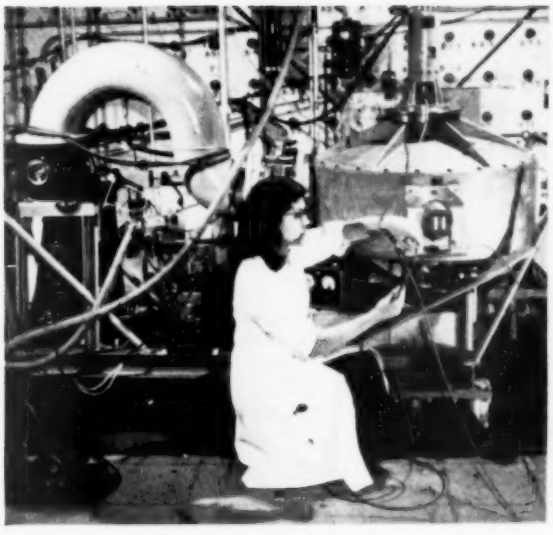
Control requirements. The over-all physical layout of the reactor shield should place the operational components so that they do not usurp space useful to research immediately adjacent to the shield. The control-rod system should be designed so that it is situated where it will least interfere with access to the reactor.

Another important feature of the control system has to do with the amount of excess reactivity which is taken up by the control rods under routine operating conditions. Control rods depress the neutron flux in their immediate vicinity, so that experiments nearby may suffer in two ways: (1) by having a lower flux than would otherwise be available; and, (2) by having the flux vary with changing positions of the control rods. Either of these is undesirable from the point of view of research, and it is an obligation of the operating staffs to do what they can to avoid such conditions.

This can be accomplished to a large extent by proper adjustments of the excess reactivity available after enough reactivity has been provided to take care of all the experimental equipment and poisons in the reactor. In equilibrium at routine operating power levels a research reactor



NEUTRON MIRROR EXPERIMENT at Brookhaven uses neutron beam from slit in reactor port at left. Mirror is in box next to slit



FAST NEUTRON CHOPPER at Brookhaven is cylinder revolving at high speed within housing. Apparatus is adjacent to reactor

should have a very minimum of potential excess reactivity to be contravened by the presence of control rods.

It often happens that the Brookhaven reactor operates routinely with no control rod or almost none inserted even partially. The regulating rod which is used for fine control of the power level is always as far removed from experimental work as is possible.

Experimental areas, services. The area adjacent to the reactor should be extensive enough to allow for all types of research problems. Each research position should have no less than 40 ft² of floor space available, with a width no less than 4 ft parallel to the shield face. There will always be experiments which require beams of considerable length between the reactor and the detectors, so that some area should be provided for distances up to 40 or 50 ft.

It is very important that the load capacities of all floors in the research area are high; about 1,000 lb/ft². The shielding of research equipment requires this.

All the usual laboratory services should be available at the reactor faces and nearby. Among these are 110-, 220-, and 440-volt regulated a-c; 110- and 220-volt regulated d-c; high- and low-pressure water, steam and air; drain lines or gutters for nonactivated water; drain lines tied into some monitoring point for holding up activated or contaminated water or solutions; distilled water; and a vacuum line.

There should be a somewhat isolated and enclosed area nearby for the storage and disassembly of active or contaminated research equipment and the great variety of handling tools and equipment necessary around the reactor. There should also be additional storage and disposal facilities far removed from the reactor building for active and contaminated items.

In areas of high humidity conditions, it is imperative that the building be air-conditioned for electronic equipment to operate satisfactorily.

RESEARCH FACILITIES

The research done with a reactor or its products can be divided into three categories:

1. Beam experiments. A stream of neutrons is allowed to emerge into equipment set up external to the shield.

2. "In-pile" experiments. The effects under study take place wholly within the reactor or shield, with or without control, monitoring, or recording lines coming out through the shield to external devices.

3. "Removed" experiments. These make use of only irradiated materials, and need not necessarily be conducted at the reactor.

All three types of experiments require holes or ports through the shield which connect with channels leading through the reflector and active fuel element portions of the reactor. Somewhere along the length of the holes it is usually necessary to place some kind of beam-restricting device such as a collimator, filter, shutter, or a target component. The holes themselves are usually a few inches in cross sectional dimensions, and must be accurately aligned for easy placement or removal of equipment. For in-pile experiments, special shield plugs are needed for the holes to allow for the passage of lines through them via labyrinths that prevent radiation from escaping.

Irradiation facilities. Many different facilities are required to handle radioisotope production and other irradiation needs. The great bulk of the small target work can be handled satisfactorily in conveyor systems operating either mechanically or pneumatically. Short-half-life materials are usually handled by a pneumatic system having transit times in or out of the reactor of the order of a second. Only one target carrier can be handled at one time. A mechanical system can handle hundreds of samples in a chain, and each position can be loaded or unloaded independently of all others. Brookhaven has such a system with 300 separate positions which can be loaded or unloaded at any time without interfering with the operation of the reactor.

There are many irradiation jobs which cannot be done in either of these systems because of the large physical size of the target materials, or some special condition under which the irradiation must be carried out, or the large amount of radioactivity involved. Industrial companies, doing wear tests, are now presenting targets as large as 14-in. diameter piston rings for irradiation. Brookhaven has one hole

RESEARCH with Reactors

CROSS-SECTION MEASUREMENTS. *Usually beam experiments; whole range of neutron energies covered with different apparatus, each operating effectively in narrow energy band. From 0.0005 to 0.1 ev, slow chopper or velocity selector; from 0.05 to 50 ev, single- or double-crystal spectrometers; between 10 ev and hundreds of kev, fast choppers. At higher energies, U^{235} converter device gives fission spectrum, but results pertain to average of whole fission spectrum.*

SOLID-STATE STUDIES. *In-pile studies of radiation-produced changes in physical properties require irradiation facilities operable in wide range of temperatures. Samples analyzed after irradiation or measurements made while in reactor. Neutron spectrometers give diffraction patterns, scattering, reflection, polarization data in beam studies of neutron interactions with structures of materials.*

NUCLEAR PHYSICS. *Includes work on intrinsic properties of neutrons, capture gamma-ray production, metastable or isomeric states of nuclei, properties of radioisotopic species such as half-life, decay schemes, types and energies of radiations. Equipment can be very specialized; spectrometers, beta-ray spectrographs, cloud chambers, and combinations of electric and magnetic fields often used.*

SHIELDING STUDIES. *Bulk of this work at reactors classified; devoted to particular problems on proposed reactor applications. Cross-section, capture gamma-ray studies of primary concern to shielding problems.*

LIFE SCIENCES. *Irradiate animals and plants in mutation studies, dosage tolerances, effects on growth cycles, other phenomena. Beam of reactor neutrons used to induce (n,α) reaction in boron localized in metastic tumors in human patients. Large variety of radioisotopes also used in biological and medical clinical studies.*

. . . on Reactors

Reactors now in operation, or critical assemblies, used to obtain information needed for design parameters of new reactors now in research and development stages. All such work is classified. Declassifiable research includes studies of fission-product yields, delayed neutrons, some lattice parameters.

which can handle objects of this size. For objects up to 4 or 6 in., the experimental holes or the fuel bearing channels can be used for irradiations. Here, also, the irradiations involving large amounts of radioactivity are placed where special, thick shields can be employed in removing them from the reactor.

Controlled temperature. Many activation problems presented impose limitations on temperature conditions during the irradiation. Since the ambient temperature in the Brookhaven reactor is about 150 to 175° C, it is necessary to have special facilities where the temperature is limited. One facility holds the temperature at 30° C, several others at 50° C, others at 80 to 100° C, and a system is under construction which will provide a temperature of about −190° C for solid-state work. When high temperatures are required, electrically-heated furnaces are installed to enclose the target materials.

Gaseous samples. Another facility is used for activating gaseous samples without the need for activating a container enclosing the sample.

Neutron energy for irradiation. When irradiations are requested in a highly thermalized flux, or with very low gamma-ray intensities, they are usually done in the thermal column. For a fast-neutron irradiation a uranium doughnut, previously described, is used. There are also research programs which demand large areas of leakage neutrons, and for this it is essential that pieces of the shield be removable.

Commercial availability. All these facilities for use in a reactor have to be specially designed and built. It is almost useless to attempt to find commercially available products of this type which can be adapted as units to the particular needs of reactor research. If a furnace is to be installed to provide high temperatures, the easiest thing to do is to build it as an integral part of the setup which goes into the reactor.

HANDLING TOOLS, EQUIPMENT

There is a great variety of handling tools and equipment needed around a reactor for use in connection with both research projects and operational functions.

Operational tools. Many tools needed to maintain the reactor in operation are usually tailored to a particular reactor and are of no concern here. Others, such as periscopes, borescopes, portable and overhead cranes, battery-operated small trucks, and vacuum cleaning equipment are common essentials to all reactors.

These items are commercially available, and, in most cases, can be used without modification. The periscopes and borescopes used for remotely viewing or examining things inside the reactor may have to be especially built because of their unique physical dimensions, but functionally they are similar to catalog items. A borescope, for instance, might have to be 40 ft long and pass through a bore $\frac{1}{2}$ in. in diameter.

Research needs. For research, many tools and equipment are also tailored to particular experiments, but there are numerous general requirements. Large quantities of lead bricks and "stockable" shielding blocks are obvious. Portable, shielded caves of many sizes and shapes are needed for removing radioactive objects from the reactor. One or more such caves should contain an internal reel onto which lengths of radioactive wire (thermocouples, etc.) and tubing can be wound. With the caves, a number of portable, load-carrying platforms, capable of being adjusted to a range of heights, are necessary.

Long-handled tools for manipulations over long distances are essential. Numerous sizes and shapes of shielded containers for the transport and storage of radioisotopes are required. All kinds of survey meters for the detection of radiation are needed in large quantity and in various ranges.

Reactor canal. Reactors generally have a large water-filled "canal" into which spent fuel elements are discharged for safe handling, or storage. Such a canal is also essential for doing manipulative research jobs where it is necessary to see what is being done while being afforded the shielding protection of a thick layer of water. As with fuel elements containing enormous quantities of radioactivity, large radioisotope sources are most easily handled under water in operations prior to and including their placement into containers for moving.

Favored Reactor Types

Group	Fuel	Neutron energy	Coolant	Moderator	Electric power output (Mw)
Commonwealth—Public Service	Natural uranium	Thermal	D_2O	D_2O	225
P. G. & E.—Bechtel	U^{235}	Fast (breeder)	Liquid sodium	—	145
Monsanto—Union Electric	Enriched uranium	Thermal	Liquid sodium	Graphite	210 or 550
Dow—Detroit Edison	U^{235}	Fast (breeder)	Liquid sodium	—	135

Nuclear Power Feasibility Studies

A year of study by four industrial teams has led to the design and cost data presented here for reactor powered electrical generating stations. The type of reactor that each group favors is shown in the table above

SUMMARIZED HERE are four reports just declassified by the Atomic Energy Commission. The reports resulted from separate one-year studies of classified reactor technology carried out by four industrial teams: Commonwealth Edison Co. and Public Service Co. of Northern Illinois; Dow Chemical Co. and Detroit Edison Co.; Monsanto Chemical Co. and Union Electric Co.; and Pacific Gas and Electric Co. and Bechtel Corp.

The studies represent the first non-government analysis of industrial nuclear power. All four groups concur in the belief that dual-purpose reactors are technically feasible and could be operated in such a fashion that the plutonium credit would reduce the cost of power. Conversely, all agree that no reactor could be constructed in the very near future which would be economic on the basis of power generation alone. But all four groups expressed a willingness and a desire to continue their efforts with more detailed studies and the development of components.

The studies were made according to certain conditions, one being that the groups should consider the possibilities for dual-purpose reactors. Consequently, the designs settled on here are not necessarily those which would have been selected had the studies been directed toward power-only reactors with the plutonium produced having but fuel value.

Another is the requirement of the agreements specifying studies of designs for reactors that might be built within the next few years. Thus the companies for the most part directed their efforts to conservative concepts, components of proved design, and conditions reasonably certain of early fulfillment.

It should also be realized that in the short time for the studies and because of the limited reactor experience of many of the engineers, the reports could not be detailed architect-engineering plans but rather preliminary evaluations or feasibility studies by engineers and management men.

Because of security limitations, the material contained in the following pages also does not present a balanced picture of the original reports. Very little specific reactor design and economic data could be included.

In varying degrees, all of the groups are continuing their studies. It should be emphasized that as these studies continue the designs described here will be modified considerably to incorporate the best available knowledge.

At present, the most active groups are probably Dow-Detroit Edison and Monsanto-Union Electric. Commonwealth Edison-Public Service recently submitted a second and as yet classified report on the type of reactor in which they are most interested, a water-cooled pile of similar design to that in operation at Argonne.

PG & E-Bechtel is probably the least active of the teams, but it is continuing some studies.

Detailed Cost Data ($-million)

Water-Cooled Thermal Reactor and Sodium-Cooled Fast Reactor (P.G. & E.—Bechtel)

	Thermal reactor	*Fast reactor*
Site	0.70	0.70
Site improvement	2.10	2.10
REACTOR CAPITAL AND OPERATING COSTS		
Structure:		
Substructure	1.40	1.90
Superstructure	0.60	0.80
Utilities, equipment	1.25	1.30
Core:		
Tank	0.25	0.50
Piping	3.55	2.60
Thermal shield, accessories	0.35	0.90
Blanket		2.00
Heavy water ($83.00/lb)	7.00	
Sodium		0.80
Cooling circuit:		
Piping, controls	2.45	3.00
Pumps, equipment	1.10	4.50
Steam generators	2.80	3.50
Auxiliary circuits:		
Pure water	0.80	0.30
Heavy water	0.75	
Sodium		3.00
Helium		0.50
Controls	0.85	1.50
Fuel handling	1.20	6.00
TOTAL REACTOR CAPITAL COST	24.35	33.10

	Thermal reactor	*Fast reactor*
Personnel:		
Operation	0.253	0.253
Health physics	0.08	0.08
Technical services	0.078	0.078
Security	0.088	0.088
Administration	0.036	0.036
Supplies	0.05	0.05
Heavy-water makeup ($7,000,000 at 5%)	0.35	
Maintenance (1% of capital excluding heavy water)	0.17	0.33
General expense (15% of operation and maintenance)	0.115	0.14
TOTAL REACTOR OPERATING COSTS	1.22	1.055
POWER PLANT CAPITAL AND OPERATING COSTS*		
Capital cost	12.65	13.60
Operating costs:		
Operation ($1.70 per kw-yr)	0.18	0.265
Maintenance (1% of capital)	0.13	0.14
General expense (15% of operation and maintenance)	0.05	0.06
TOTAL POWER PLANT OPERATING COST	0.360	0.465
Step-up facilities	1.20	1.50
TOTAL CAPITAL COST	41.00	51.00
TOTAL ANNUAL OPERATING COST	1.58	1.52

* Water-cooled reactor, 106.2 Mw; sodium-cooled reactor, 154.6 Mw.

Gas-Cooled Reactor (Commonwealth-Public Service)

REACTOR	
Concrete shell and sphere in place	$1.04
Cast-iron plate lining	0.7
Bolts for lining	0.1
Cadmium-silver plating	0.1
Fuel loading	2.0
Instrumentation and controls	1.2
Raw graphite, 2,400 tons	1.0
Finished graphite, 2,100 tons, machined and installed	1.26
Elevators, charging equipment	0.3
TOTAL	7.7
BOILERS	
Duct work and piping	0.5
Valves	0.42
Blowers, helium circulation	1.2
Boilers, 12	1.2
Misc. foundations, etc.	0.28
Control equipment	0.225
Demineralizing plant	0.125
Boiler-room crane	0.075
TOTAL	4.025
Turbogenerator	4.305
Stack, 500 ft high	0.5
Water system, decontamination area and waste storage	0.1
Buildings	4.2

HELIUM SYSTEM	
Helium	0.15
Clean storage	0.4
Dirty storage	0.4
Substorage	0.32
Purification, including buildings	0.2
Misc. piping and equipment	0.18
TOTAL	1.65
Deepwells, 2	0.1
Electric plant	0.975
Transmission terminal	0.75
MISCELLANEOUS	
Operating tools and materials	0.2
Spare parts	0.3
Temporary construction facilities	0.3
Health physics instruments	0.15
Yard improvements, guard towers, fence, lighting	0.225
Site (minimum 100 acres)	0.05
Other land costs for control of safety area; recommended ground area, 2,400 acres*	1.5
Research and development costs	1.5
Contingencies	4.42
Engineering, 5%	1.7
TOTAL	9.395
Total direct cost	34.65
Overhead, 15%	5.35
GRAND TOTAL	40.00

* Safeguard Committee formula suggests area owned to be 70,000 acres, $42-million.

Liquid-Cooled Reactor (Commonwealth-Public Service)

Reactor	$ 3.846
D_2O system	3.172
D_2O at $82.00/lb	41.0
Helium system	0.23
TOTAL	48.248
Steam-generator plant	4.178
Turbogenerator plant	14.285
Structural plant	10.024
Misc. power-plant equipment	0.342
Electric plant	4.513
Transmission plant	1.0
Site	0.125
Other land costs	1.5
Yard improvements	0.83
Operating tools, etc.	0.3
Spare parts	0.5
Health physics	0.15
Temporary construction	0.96
TOTAL	38.707
Research and development	2.5
Contingencies	8.7
Engineering	4.5
TOTAL	15.7
Total direct cost	102.655
Overhead, 15%	15.345
GRAND TOTAL	$118.0

Commonwealth Edison—Public Service

THE THREE primary design objectives selected for the two reactors described were (1) the production of plutonium and electric power, (2) the use of natural uranium fuel, and (3) the maximum utilization of proved reactor technology. The two reactor types chosen are a gas-cooled, graphite-moderated plant and a heavy-water-moderated and -cooled reactor.

GAS-COOLED GRAPHITE-MODERATED REACTOR

This reactor could be built with a minimum of developmental work.

Fuel Elements

In the proposed reactor, the fuel slugs are made of uranium metal with a center hole and provided with fins which rest on the surfaces of the slug channels in the reactor core. It was assumed that heat is generated uniformly within the volume of the metal, and the design was aimed at uniform heat flow from all parts of the surface. The maximum internal metal temperature is limited to 1,000° F to prevent transformation into the β-phase.

A special method of casing the fuel elements, which on preliminary test was shown to be quite effective, is proposed. Further investigation is necessary before a final design is acceptable. An appreciable increase in reactor power could be obtained by developing an alloy and a method of casing which would permit an increase in fuel-element internal temperatures from the 1,000° F limit established in this report, up to about 1,300° F. Predominant factors in setting the 1,000° F value are the phase transformation that occurs in uranium at 1,200° F and the melting point of the proposed alloy casing.

Coolant

Helium was selected because it is chemically inert and has a zero neutron-absorption cross section. It also has a relatively high specific heat but a very low density.

For operation at a pressure of 10 atm, the design calls for a total heat output of 350 Mw, a helium inlet temperature of 450° F, an outlet temperature of 742° F, and a helium flow of 3.27×10^6 lb/hr.

Since the pumping power requirements for circulating the gas are directly proportional to the volume, pressurizing the helium materially decreases the power required to transfer a fixed quantity of heat. Allowable stress limitations of the enclosing steel sphere, and increased difficulties with seals and valves at higher pressures, serve to set the 10-atm pressure used in the system.

Reactor Shell

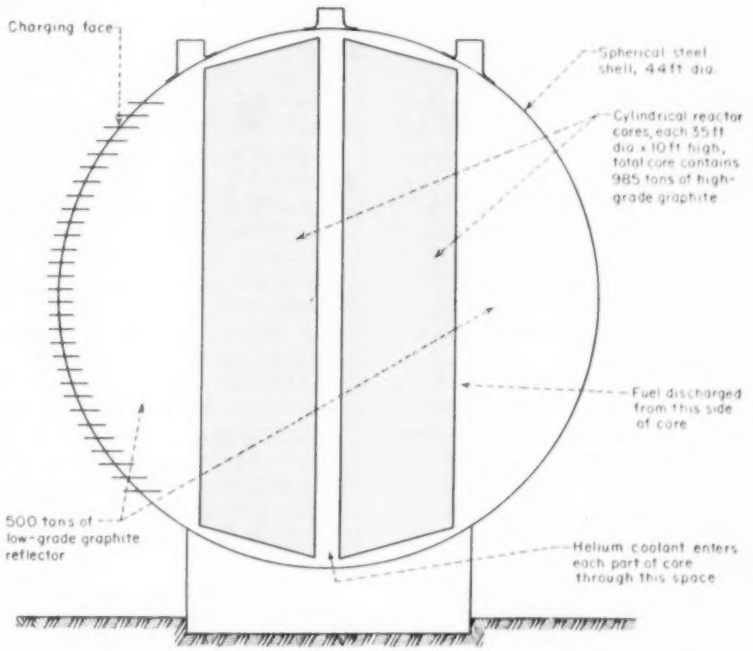
The sphere is made of formed and welded 1.67-in.-thick SA 204 grade B low-alloy steel. A rectangular concrete pad, about 25 by 21 ft, supports it.

The entire outer surface of the sphere is sand blasted and then is metal sprayed with a 70% silver- 30% cadmium alloy. This coating is applied to reduce the neutron flux leakage at the surface of the sphere and the resultant irradiation of the air inside the biological shield. This treatment is also applied to the helium piping outside the sphere.

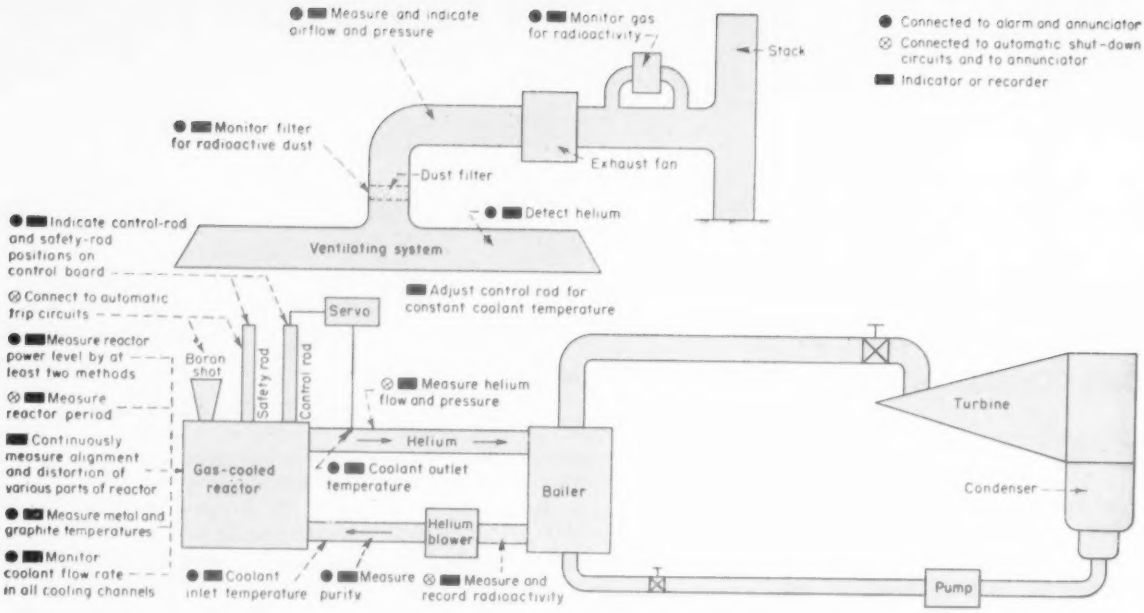
Shielding and Ventilation

The radiation shield will completely enclose the sphere containing the reactor. It is made of crushed-limestone-aggregate concrete to obtain maximum resistance to heat. The shield beneath the sphere is a 10-ft-thick heavily reinforced concrete foundation pad. Adjacent to the charging face of the sphere and 10 ft away from it is a vertical 8-ft-thick concrete wall supported on rollers to move with the expansion of the charging tubes which pierce it and the sphere.

At the rear of the sphere and 6 ft away from it is another vertical 8-ft-thick concrete wall. The other two sides and the top of the sphere are en-


Charging face
Spherical steel shell, 44 ft dia
Cylindrical reactor cores, each 35 ft dia x 10 ft high; total core contains 985 tons of high-grade graphite
Fuel discharged from this side of core
500 tons of low-grade graphite reflector
Helium coolant enters each part of core through this space

HELIUM-COOLED REACTOR is contained in steel sphere. System for charging and discharging fuel slugs can operate without reactor shutdown



INSTRUMENTS AND CONTROLS for helium-cooled graphite-moderated reactor system. Devices connect to alarms, automatic shutdown mechanisms, indicators, or recorders

closed by an arched 8-ft-thick concrete shell starting from and ending at the foundation pad. This arch extends over the outside surface of the end walls and is flush with it. The joint between the end walls and the inner surface of the arch is staggered to prevent radiation leakage.

The inner surface of these shield walls and the floor are covered with 6-in.-thick 1-ft-square cast-iron plates supported by 1-in.-diameter steel bolts passing through a central hole in each plate.

The helium leaving and entering the reactor passes through the biological shield through special 30- by 24-in.-diameter shield duct sections. These are designed to reduce the intensity of the direct neutron beam that escapes through the ducts.

Every effort is made to keep outward radiation leakage from the sphere shield and inward air leakage to a minimum. The air inside the shield is hot because of the temperature of the sphere surface, the cast-iron plates, and the inner surface of the concrete. This temperature is used effectively to cause the hot air to rise in a stack and maintain the interior of the shield at a negative pressure so that all air leakage is into the shield. This leaking air becomes radioactive and requires dilution prior to being discharged from the stack.

Charging and Discharging

A reactor charging and discharging system capable of operating without reactor shutdown is used. Without it, the availability of the electrical generating equipment is reduced. Also, if the entire contents of a channel need not be removed each time it is charged, the quantity of plutonium produced per pound of metal charged is increased.

By means of the charging machine, the outer half of the charge in the spherical segment nearest the charging face is pushed through the graphite and becomes the outer half of the charge in the spherical segment away from the charging face. The inner half of the charge in each spherical segment of the graphite is fresh uranium identical to the outer half of the charge nearest the charging face when the new charge is installed. This sequence provides even exposure since the neutron intensity is lowest at the entering and leaving faces of the spherical sections of graphite and is greatest in the center.

The irradiated slugs drop out of the core on the far side and accumulate at the bottom of the sphere, where they are removed to the storage canal through an opening with pressure locks.

It is possible to charge two channels at a time by the use of a six-cylinder charging machine in a sequence operation. The charging cylinders move their charge into the sphere by helium pressure and are ejected by the internal-sphere helium pressure.

The additional uranium inventory in the charging area, the cool-off storage, plus a 90-day reserve, amounts to somewhat more than half of the reactor loading. About the same amount of additional uranium is required each year for the reactor operation.

Heat-Transfer System

Helium cycle. The helium is heated in passing through the reactor and then passes through boilers where feed water is converted into superheated steam. The inlet temperature of the cycle is 650° F, and the outlet temperature is 384° F. Helium is circulated at a rate of 3.27×10^6 lb/hr, and the total heat released is $1,085 \times 10^6$ BTU/hr.

The helium is returned from the boilers to the reactor by means of blowers. To keep ducts reasonable in size, 12 separate circuits, each consisting of duct work, a boiler, and a blower, constitute the design.

Boilers. Ten boilers are required to absorb the heat from the helium gas. The boilers used are the straight-

through type in which economizer, generator, and superheater sections are combined into one continuous pass.

The steam output for each boiler is 90,600 lb/hr at a temperature of 525° F and a pressure of 250 psig.

Blowers. Axial-flow type blowers, which must be operated at constant flow, are used. Variations are only possible in increments equal to the capacity of one blower. Boiler load variations within the range of a given number of blowers are obtained by allowing deviations in the helium exit temperature.

Suitable double-bellows shaft seals, to minimize helium leakage, and bearings capable of continuous operation at 400° F are used. The capacity of each blower is 75,000 ft³/min.

Turbogenerator

Consideration of the helium inlet temperature of 650° F to the boiler in relation to a practical corresponding steam temperature set the value of 525° F for steam. The pressure, without exceeding the accepted 14.7% moisture limit, is then 265 psia. The conditions are within the acceptable range for low-pressure sections of modern cross-compound machines.

With 15,000 kw of electric power used for auxiliaries, the net generation is 46,700 kw.

Calculations show that, if the heat output of the reactor is kept constant, the reduction in auxiliary power with increased fuel temperature would produce a 29% increase in net power available to the system with no increase in plutonium production. However, if the weight of helium circulated is held constant instead, the net power available is increased by 113%, and plutonium production is also increased.

Control system. The system for control of this reactor power plant has the following features:

1. Reactor outlet helium temperature is kept at a constant 750° F by automatic control-rod adjustment.
2. Boiler rating is varied by adjusting feed-water flow.
3. Helium flow is held constant at full blower load for those boilers in service. As the boiler rating is varied, the boiler outlet gas temperature changes instead of the helium quantity.
4. Boiler output determines kilowatt generation. Steam temperature varies from design value of 525° F at full rating to a theoretical value of 650° F at zero rating.
5. Turbine control valves are adjusted by steam-pressure controller.

To be able to maintain the reactor at full power rating and obtain high plutonium production even while electric generation is reduced, a steam bypass line to the main condenser is used. This condenser can dissipate the total reactor heat output. The bypass action is automatic and protects the reactor in the event of a turbine trip-out.

LIQUID-COOLED LIQUID-MODERATED REACTOR

The reactor unit, enclosed in a spherical steel shell capable of withstanding a pressure of 800 psia, uses heavy water as coolant, moderator and reflector. The fuel assembly is composed of a number of separate fuel elements each consisting of an assembly of uranium elements in a thin metal casing. These fuel assemblies are placed in cylindrical channels. Heat generated in the uranium is transferred through the thin metal cladding to the heavy water which is traveling parallel to the uranium elements in a vertical direction.

The heavy water is used both as moderator and coolant. The D_2O returning from the steam generators is directed under a stainless-steel tube sheet, into which the fuel channels are set. It then flows upward through the fuel channels and also between the fuel channels. The D_2O between fuel channels, which acts as the moderator, travels relatively slowly and discharges from the reactor through the control-rod assemblies.

The reactor core is essentially a right cylinder contained in a spherical pressure shell. The fuel elements, hanging vertically in the channels, are charged and discharged from the top of the cylinder.

The design maximum surface temperature of the fuel elements is 465° F when the reactor D_2O outlet temperature is 440° F. Therefore, the uranium cladding and the tubes, both located in the reactor core, must withstand these temperatures.

Charging and Discharging

The reactor will be shut down about 12 hr before the discharging and charging operations are begun. Both operations will proceed together using a Gantry-type traveling crane and a lead coffin. The spent fuel elements are carried by the coffin and crane to a water-filled trench, where they are discharged and then transported under water to the area that is used for storage and shipping.

Fresh fuel elements are placed in the coffin, which is aligned again over the open fuel channels, and the new elements are lowered into position. The control-rod tube need not be removed during the charging and discharging operation.

Shell

The reactor shell is designed to contain the fuel elements, control rods, moderator, and reflector. It has inlet and outlet openings for the coolant and is able to withstand internal pressure.

The heavy-water coolant flow at maximum load will be 303.3 ft³/sec. With a flow velocity of 25 ft/sec, the inlet openings have a total effective cross section of 12.1 ft². They are spaced evenly around the periphery of the shell to provide uniform flow into fuel elements and around fuel elements and control rods.

Even distribution of the coolant is obtained by using nine inlet openings evenly spaced around the periphery of the shell. The fuel-element and control-rod tubes are utilized as coolant outlets.

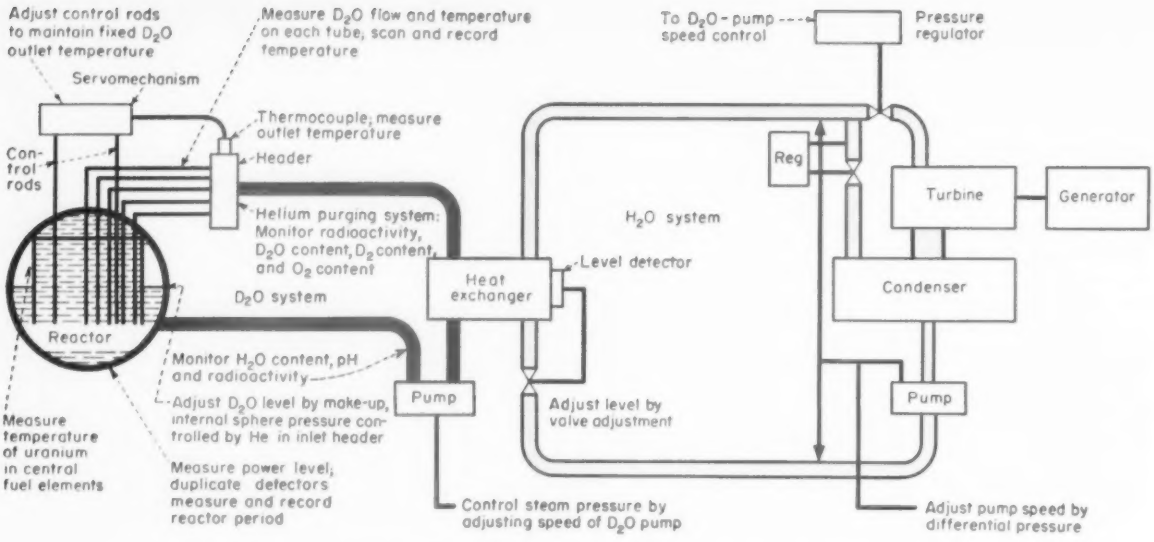
The spherical shell is 2.14 in. thick and 20 ft, 4 in. in diameter. It is fabricated of type 347 austenitic stainless steel to prevent corrosion of the shell and contamination of the heavy water. The inner cylinder and the connections to the sphere, i.e., fuel-element charging tubes, control-rod tubes, water-inlet piping, helium-pressurizing piping, and drain pipe, also will be made of type 347 austenitic stainless steel.

Helium Purging System

Provision is made for a helium-blanketing system wherever there is an interface in the D_2O circuit. These interfaces exist in the reactor sphere outside the cylinder (expansion segment) and above the D_2O in the dump tanks and make-up tank.

Radiation Shielding

The radiation shielding for the reactor is made of 8-ft-thick reinforced


Adjust control rods to maintain fixed D_2O outlet temperature
Servomechanism
Measure D_2O flow and temperature on each tube, scan and record temperature
To D_2O - pump speed control
Pressure regulator
Thermocouple; measure outlet temperature
Header
Con-trol rods
Reg
Turbine
Generator
Helium purging system: Monitor radioactivity, D_2O content, D_2 content, and O_2 content
H_2O system
Level detector
Heat exchanger
Condenser
D_2O system
Reactor
Monitor H_2O content, pH and radioactivity
Pump
Adjust level by valve adjustment
Pump
Adjust D_2O level by make-up, internal sphere pressure controlled by He in inlet header
Measure temperature of uranium in central fuel elements
Measure power level; duplicate detectors measure and record reactor period
Control steam pressure by adjusting speed of D_2O pump
Adjust pump speed by differential pressure

BASIC INSTRUMENTATION AND CONTROL FUNCTIONS for liquid-cooled liquid-moderated reactor system. Primary coolant is in black, secondary coolant is in gray

concrete, using limestone aggregate. Reinforcing in this concrete is the minimum necessary for the required structural strength.

The inner and outer surfaces of the shield are lined with steel. The inner steel skin is 1 in. thick, the outer skin ¼ in. thick. The concrete-reinforcing steel is placed to hold the inner and outer steel shield surfaces as forms for the concrete.

The reactor pressure vessel is supported inside the shield by stainless-steel brackets attached to its central circumference. These brackets rest on rollers which bear on steel plates set in the shield. The rollers are designed to move with the radial expansion of the reactor pressure vessel.

The vertical fuel-element charging tubes, the vertical control-rod tubes, and the horizontal water-discharge pipes leading from these tubes to the headers form a large part of the top shield. The top surface of the upper shield forms the charging floor.

The shielding in the remainder of the plant, around the steam generators, piping, pumps, and miscellaneous storage tanks, consists of 3-ft-thick concrete floors, walls, and ceiling. The steam generators and pumps are arranged in individual cells.

Access to the cells is through plug-type trap doors. When repairs are necessary, the particular piece of equipment is isolated from the D_2O system by motor-operated shut-off valves. The D_2O is drained to the activated D_2O storage tanks, the motor-operated D_2O drain valve is closed, and light water is run through the equipment until activity is reduced to a safe level for men to enter the cell.

Control and Instrumentation

Fuel-tube monitoring. The amount of heavy water flowing from the reactor is monitored as is its temperature at each fuel-tube outlet and control-rod opening. A manually operated valve on each tube serves as the adjustment of the flow distribution over the reactor lattice area. Flow adjustments are made on the basis of temperature measurements of the water at each tube outlet.

A pressure tap on each fuel tube supplies the flow data. Flow changes indicate defects, such as clogged fuel tubes resulting from warping of fuel elements or wall leaks in a fuel tube. Flow-valve adjustments change the readings from the pressure taps and set new bases for comparison to determine abnormal conditions.

A rapid-scanning device for measuring and recording the temperatures and pressures serves to localize any defects which develop. The scanning equipment has limit settings to initiate an alarm and cause automatic shutdown of the reactor when the limits are exceeded.

Thermocouples are the only means of detecting localized hot spots in the fuel elements; therefore failure of both thermocouples on any tube is cause for reactor shutdown. Also, a defective flow detector is considered a serious hazard.

In addition to the thermocouples connected to the individual fuel-element tubes, there are several thermocouples in the hottest area of the reactor to measure and record the uranium-metal temperature. The temperature of the D_2O at the inlet to the reactor is recorded.

Heavy-water leakage from seals and valves is continuously collected by a gravity piping system. Leakage at gasketed joints and other suspected locations is monitored by permanently located probes connected to electronic detectors.

Control and safety rods. The control rods are 1.5% boron steel, clad with stainless steel to resist corrosion. Guide tubes provide an alignment channel to ensure against jamming of the rods in the tube sheets or shifting of their position by the flow of the coolant. Coolant flow in the space between the guide tube and the control rod dissipates the heat generated in the rods.

Certain of the control rods are used to control the operating level of the reactor. They are actuated in unison by a servomechanism which receives its

input signal from the summation of thermocouples located in the main D_2O outlet header of the reactor.

To simplify mechanical arrangements on the top of the reactor, the control-rod operating mechanism is mounted below the sphere. It is a type of linear motor utilizing a magnetic field acting through the nonmagnetic walls of the pressure thimble and positioning a magnetic slug fastened to the control rod. The rods not used for automatic control are adjustable to compensate for reactivity changes. Their mechanisms allow them to act as combination safety and shim rods.

The reactor power level is determined by three methods: boron-coated ionization chambers, boron thermopiles, and the heat-flow instruments on the reactor.

Heat-Transfer System

To minimize the amount of coolant holdup in the piping, a flow velocity of 25 ft/sec was selected, and the length of piping was held to a minimum by arranging the steam generators in a tight circle around the reactor, as shown in the cover picture.

Steam-generators. With a 1,064-Mw reactor heat output, three turbines are desirable, and the steam generators should be of such a capacity that the total number of units is an even multiple of three. The accepted design produces 180,000 lb of 180-psia, 373° F saturated steam per hour from each of 18 units. These are arranged in pairs to reduce the number of coolant pumps and valves.

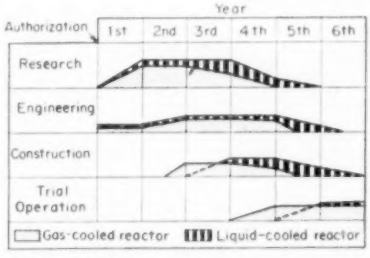
Coolant-circulating pumps. The coolant-circulating pumps presented one of the major design problems. This problem results from a combination of the large flow quantities to be delivered, the high suction pressure that must be sealed, the essentially low gland leakage, the high liquid temperature, and the radioactivity in the coolant. The pumps were designed of stainless steel for a total coolant flow of 68.84×10^6 lb/hr, and a pumpage of 15,300 gal/min.

A small external leakage from the gland exists and is collected; the annulus is connected to a drain. The gland-seal coolant is supplied from the discharge of each pump, passing through a small heat exchanger before entering the gland. The drains are returned to the make-up tank.

The pumps used are a single-stage overhanging-impeller design with the one gland exposed to the suction pressure. Because of the high temperature of the liquid, flashing would occur in this gland. Coolant at 100° F and at a pressure above the suction is circulated to an intermediate position in this gland. This causes a flow of the seal coolant along the shaft through labyrinthine packing into the pump in one direction and into an annulus in the opposite direction. A flow of approximately 5 to 10 gal/min of seal coolant is required.

Coolant storage and make-up system. Four storage tanks, with a total capacity of 62,000 gal, provide for the dumping of all coolant. These tanks are lined with stainless steel and have a helium blanket to minimize contamination.

The make-up system for the coolant includes a tank, pumps, filters, and a demineralizer. The pumps act to return all valve-gland leakage to the 800-psia coolant system in addition to their function of filling the system.



TIME SCHEDULES for work on gas-cooled and liquid-cooled reactors

Coolant-treatment system. Heavy water exhibits the corrosive characteristics of light water at similar temperatures and pressures and must be chemically pure to inhibit radioactivity.

Since the water contains dissolved solids which are irradiated in the reactor and deposited in the water-treating system, it is necessary to shield each section with 4-in.-thick lead blocks.

Turbogenerator Units

Turbogenerator units were designed for use with 175-psia, 371° F steam at the turbine throttle.

The maximum commercial size turbogenerator which is available for the particular steam conditions is 80,000 kw. Three of these are used.

Cost Estimates

An analysis of the figures given in the table on page 50 shows that approximately 40% of the cost is for D_2O and 20% is for the reactor, including the D_2O system, controls, and additional land and site development. The remaining 40% approximates the cost of the parallel plant components of an equivalent conventional steam turbogenerator plant.

If the reactor were designed for light-water cooling and moderation, which would require the use of enriched fuel, the initial investment could be reduced by about $47-million. The cost per kilowatt of electric generating capacity would be reduced from $492 to $297.

These costs are based on the assumption that fabricated fuel elements are furnished by others; also, the cost of initial fuel charge is not included.

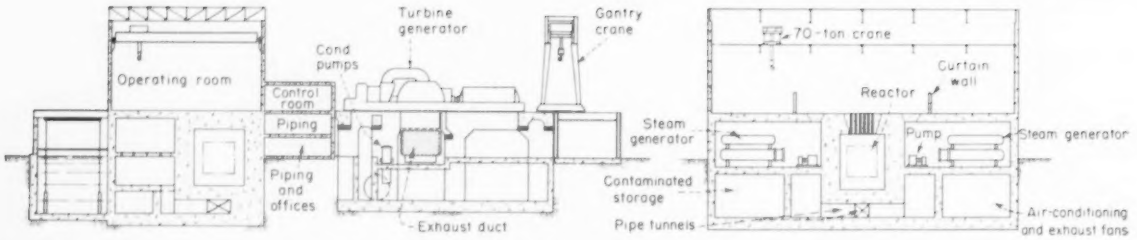
Conclusions

On the basis of our investigation, and considering the present status of reactor technology, we feel that the heavy-water-reactor concept has the best economic possibilities. The important uncertainties are the availability and cost of heavy water and the practicality and cost of a chemical plant to process fuel elements.

Considerable advantage may be gained by the use of light water for moderator and coolant if uranium with a sufficient degree of enrichment can be obtained. The future cost of enriched fuel and the dependability of its supply are uncertainties which would have to be resolved, of course.

However, the gas-cooled reactor could provide a substantial beginning in atomic power with a minimum of interference with production reactors now under construction or contemplated. The fuel elements should be less costly than some of those used in production reactors, and they can be processed in existing chemical plants.

It is the opinion of this group that both reactor designs described in this article are feasible from engineering and operating standpoints and that, assuming the availability of critical material, research facilities, and manpower, the research, final design, and construction could be carried out substantially in accordance with the time schedules drawn up.



SUGGESTED LAYOUT of nuclear power plant using water-cooled thermal reactor (side view at left, end view at right)

Pacific Gas and Electric—Bechtel

IN A CONSIDERATION of the various reactors for the purpose of producing power and fissionable materials, it is practical to include an evaluation of each reactor in terms of the ultimate requirements of a nuclear plant producing power only. In this study, therefore, the contribution of each dual-purpose reactor to the development of future power reactors has been considered.

A 500-Mw reactor was selected as a reasonable size for this study. The corresponding net power output will be 100 to 150 Mw and is roughly equivalent to the maximum feasible size of turbine units at lower pressures. It would produce significant amounts of power and plutonium and would be a compromise between a smaller developmental size and a larger, more economic size.

Two reactors were chosen for detailed study: one having immediate technical feasibility and the other having more development problems but greater promise as a future power reactor.

The light-water-cooled heavy-water-moderated reactor was chosen because it can be designed and built more quickly than other types and its cost can be predicted with some feeling of confidence. On the other hand, it is limited to low steam pressures with the associated low thermal efficiency. For this reason it is expected that the water-cooled reactor will not be the ultimate reactor that will be built for generating electricity.

The liquid-metal-cooled fast reactor was selected because of its ability to breed new fissionable material and to operate at high temperatures, both features being desirable in the nuclear-power field.

WATER-COOLED NATURAL-URANIUM REACTOR

Essentially, the reactor consists of an aluminum tank, with a multiplicity of aluminum tubes between tube sheets, serving as the container of the moderating heavy water. The fuel is placed in pressure tubes which extend through the core tank concentric to the aluminum tubes. Light water, the primary coolant, flows through these pressure tubes.

Coolant. Cooling water enters the pressure tubes from an inner-ring header, flows through the center portion of the core, through crossover pipes on the top of the reactor, and down through the outside pressure tubes into an outer-ring header. A water velocity of approximately 15 ft/sec provides adequate heat-transfer rates. Centrifugal pumps and valves are equipped with injection glands to prevent leakage of radioactive water.

The two-pass arrangement, while subject to further study, is justified on the basis that it provides the coolest water to the most active tubes, increases allowable spacing between fuel elements, and, since both inlet and outlet headers are below the reactor-core tank, loading is less complicated.

Reflector. The reflector consists of an annulus of demineralized light water 1 ft thick surrounding the core tank and 1 ft of heavy water across the top and bottom of the core tank. The light water is contained in segmental tanks. The space between tanks is occupied by control plates.

Generator. The steam generator is divided into four sections, each located in a separate shielded cubicle adjacent to the reactor. The steam produced by the generators is utilized in a tandem-compound double-flow 1,800-rpm turbine having a maximum capability of 125,000 kw.

Moderator. The moderator-cooling system, using aluminum piping, is designed to handle 7.5% of the total heat output from the reactor (37.5 Mw) and

to cool the D_2O from 180 to 120° F. The D_2O pumps must be designed for essentially zero leakage because of the high value of the heavy water.

Thermal shield. The thermal shield comprises 6 in. of iron, suitably ventilated, and a layer of material containing boron surrounding the reflector. The primary shield surrounding the reactor is completed by 8 ft of ordinary concrete. A study of construction costs reveals no economic advantage to be derived from using high-density concrete.

Controls. Control of the reactor is effected by plates, located at intervals around the periphery of the core tank, which occupy aluminum sheaths between tubes in the "in" or "pile-down" position. The plates are withdrawn from the sheath by a servomotor actuated from the control system. In case of an emergency shutdown, the plates are released from the drive motor by an electromechanical device and fall into place within the sheath.

Since the allowable radiation exposure of uranium is limited by the specifications for the fissionable material produced in the reactor, it is necessary to remove the fuel much more frequently than the demands of a power-producing plant alone would dictate. On account of this, the entire reactor charge is replaced several times per year.

LIQUID-METAL-COOLED DUAL-PURPOSE FAST REACTOR

The fast reactor has advantages for both a dual-purpose installation and the ultimate nuclear-power industry. Future improved designs could be substituted without altering the basic arrangement of the reactor power plant.

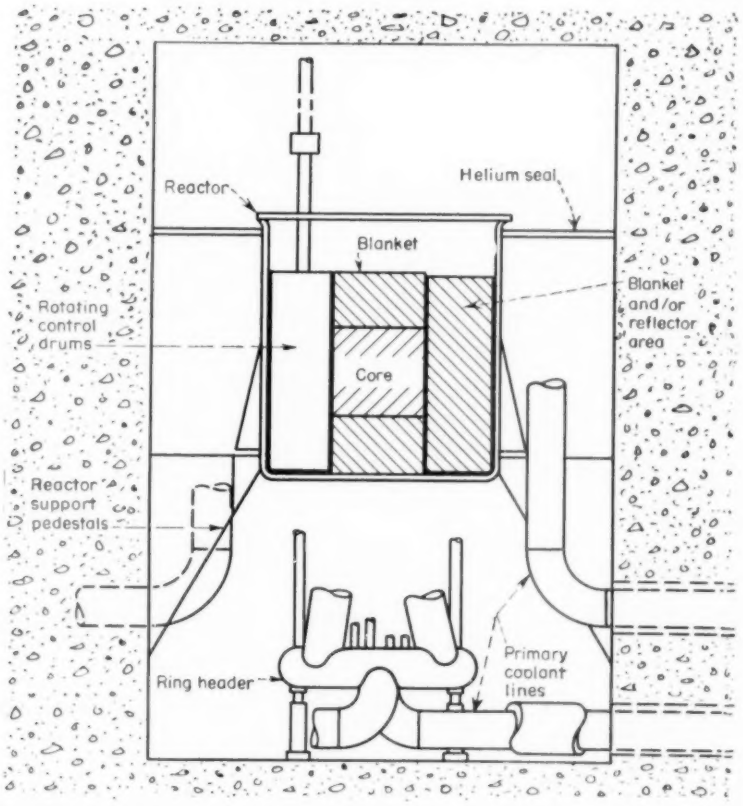
Reactor core. The reactor core of highly enriched material is surrounded by a breeder blanket, composed of either depleted or natural uranium, and a reflector. More than 90% of the heat production takes place in the core. The core consists of an assembly of a large number of stainless steel fuel elements. All the above are contained in a cylindrical steel vessel approximately 8 ft in diameter and 8 ft high. Provision must be made in the vessel for the circulation of liquid sodium, for access to permit refueling, and for the control mechanism.

Coolant and generator. Heat is removed from the reactor core and blanket by liquid sodium flowing at approximately 30 ft/sec. Circulation is maintained by two electromagnetic pumps. Primary coolant is pumped to two intermediate heat exchangers, entering them at 900° F and returning to the reactor at 600° F.

The intermediate coolant, sodium, is circulated by electromagnetic pumps to the steam generators. Secondary-coolant sodium entering the steam generators at 850° F produces superheated steam at 500 psig and 750° F. Two steam generators are required, each producing 800,000 lb hr. They each consist of a steam drum, evaporator, and superheater section. Steam is delivered to the turbine throttle at 485 psig and 750° F. The steam generator is also of single-tube construction since both sides are operated at full boiler pressure and since any mixing of sodium and water, which might result from a small leak, will not endanger reactor operation. Steam is delivered to a single large turbogenerator of 154,600 kw maximum capacity.

Controls. Control can be effected either by moving a reflector located between the core and the blanket or by altering the disposition of fertile and fissionable material. Either method can be accomplished by the use of control drums, incorporating in their most reactive position all the elements of the normal blanket (and reflector). Another possibility is a movable reflector outside the core, which can be raised or lowered to change the reactivity. A control of this type is in operation in the EBR at the National Reactor Testing Station.

Refueling. Refueling a liquid-sodium-cooled reactor is complicated by the requirement that an atmosphere of inert gas (probably helium) must be maintained over the sodium surface at all times. This means that the refueling mechanism must be positioned, reactor core and blanket exposed, spent



REACTOR CORE of liquid-sodium-cooled fast reactor. Surrounding core are natural uranium breeder blanket, reflector, and coolant lines

and irradiated elements removed, and fresh elements placed in the reactor without allowing air to infiltrate into coolant space. Although details have not been worked out, the following major operations must be accomplished in refueling:

(1) Shut down the reactor and secure the controls; (2) insert poison rods in the core; (3) lower the sodium level to expose the fuel assemblies; (4) position the withdrawal mechanism over each assembly in turn; (5) through an arrangement of locks, withdraw the assembly into a shielded cask; and (6) store the casks, maintaining adequate cooling until time for chemical processing.

Several significant features of the refueling schedule for the dual-purpose fast reactor must be emphasized. They are the following:

Complete refueling of the core and the inner portion of the breeder blanket will be required once a year. If the reactor is operating as a converter, the U^{235} remaining in the core must be decontaminated and reprocessed. If the reactor is operating as a breeder, a portion of the separated and decontaminated plutonium must be reprocessed to make up a core for another reactor.

This reactor is designed to operate with an 80% annual capacity factor. One month is provided for scheduled maintenance and refueling. Refueling will involve complete replacement of core fuel elements, and as much of the blanket as may be necessary to maintain reactivity control. The nuclear constants of the various materials appear to be favorable to this type of prolonged operation and high burn-up of fuel.

If the fuel elements contain U^{235} as the fissionable material, there should be no particular difficulty in fabricating them. After exposure in the reactor, the remaining uranium can be separated from the plutonium and, after decontamination, reduced to metal and fabricated into fuel elements without resorting to remote-handling procedures.

There appears to be little doubt that operation of the fast reactor will be more economical as a converter for a considerable period of time because of the high value of plutonium. When changing to the breeder cycle, the handling of plutonium could still be avoided by substituting U^{233} and thorium.

CONCLUSIONS, COSTS, AND RECOMMENDATIONS

It is estimated that an additional two years will be required to complete a fast-reactor installation, compared to a water-cooled thermal reactor. This time could possibly be reduced at the expense of additional and parallel development work.

The outstanding advantage for a liquid-metal-cooled reactor, as contrasted with one which is water cooled, is the possibility of improved steam conditions. For the present fast-reactor design, a throttle steam pressure of 485 psig and a temperature of 750° F have been selected. Test results to date have not revealed any limitation on the temperature of liquid sodium as the coolant.

With further experience, it appears entirely feasible that coolant temperatures may be increased to a point where steam at 1,000° F is obtained.

Estimated Costs

Capital costs for each of the two dual-purpose reactors, exclusive of fuel fabrication and chemical-plant facilities, have been estimated from the conceptual design of the reactor and power plant. All costs have been estimated on the basis of June, 1952, rates and prices.

The fixed charges used in the table on this page are typical of those for private-utility financing of conventional steam plants. Not including depreciation, the total of fixed charges for return, taxes based on income, property taxes and insurance is 10.6% (6.0%, 2.5%, 2.0%, and 0.1%, respec-

Design and Operating Data for Dual-Purpose Reactors

	Water-cooled thermal reactor	*Sodium-cooled fast reactor*
POWER		
Heat produced (Mw)	500	500
Gross electric power (Mw)	106.2	154.6
Net electric power (Mw)	100.6	145.3
Capacity factor	0.75	0.80
Millions of kw/yr (net)	659	1,018
MATERIALS		
Fuel	Nat. U, 60 tons	U^{235}
Fertile material		U^{238}
Core size	13.2 ft dia. × 11 ft high	38 in. dia. × 38 in. high
Moderator	D_2O	None
Reflector	H_2O	Pb
Shield	Concrete	Concrete
Primary coolant	H_2O	Na
COOLANT		
Primary-coolant temp.		
In (°F)	384	600
Out (°F)	500	900
Primary-coolant pressure (psig)	1,000	
Moderator temp.		
In (°F)	120	
Out (°F)	180	
Secondary-coolant temp.		
In (°F)		550
Out (°F)		850
Steam conditions		
Pressure (psig)	160	485
Temperature (°F)	378	750
Temperature coefficient of reactivity	Negative	
Control method	Plates and temp. coefficient	Blanket control

tively). Depreciation with a 5% sinking fund for amortization periods of 5, 10, and 20 yr are 18.1%, 8.0%, and 3.0%, respectively. Only the 5- and 10-yr periods are considered in estimating irradiation costs and total cost of plutonium. The 20-yr life is included for use in the study of power production only.

A dual-purpose plant will operate at full output with the maximum possible capacity factor to produce the maximum amount of fissionable material. It will be assumed for this study that such power is dependable and is worth 6 mills/kwhr for the estimated 75 to 80% capacity factor. This figure is comparable to the cost of producing power in conventional electric plants.

Cost of Pu production. The total cost of producing plutonium includes costs incurred before and after the irradiation of fuel elements in the dual-purpose reactor. These costs are the price of fissionable material, the expense of fabricating it into fuel elements, transportation charges, the cost of separating the plutonium from the irradiated fuel element, the interest on uranium inventory, and, finally, a credit for depleted uranium. Certain of these phases of the uranium-plutonium cycle are associated with, or can be absorbed by, existing private industries or government operation. In each case, costs can be converted to unit cost per gram of Pu contained.

In the table on this page, cost studies based on three types of sodium-cooled reactors operated for power only are compared to costs of dual-purpose operation and conventional steam-power costs. The assumptions which were made are:

(1) An amortization period of 20 yr for atomic-power plants; (2) an amortization period of 20 yr for fuel-fabrication plants; (3) private-utility financing; (4) core-fuel exposure unchanged, but blanket-material exposure increased; (5) a capacity factor of 80%; (6) no inventory charge for fissionable material (this is consistent with the assumption of no market for plutonium); (7) in Case III, power output increased 10% due to improved steam conditions; (8) in Case III, fuel-fabrication and chemical-processing costs reduced to one-third; (9) in Case II, chemical-processing and fuel-fabrication facilities also carry no fixed charges.

The power-only reactor, Case III, might reasonably be expected to reduce costs through improved technology, operating experience, and construction of a large block of power (e.g., 500,000 kw net) at one site.

Capital cost adjustments to conditions of Case I would be: site and yard improvements, owing to the development of one site being prorated to several plants; reactor, owing to construction of several units at one time, improved technology, and simplification; power plant, owing to construction of several units at one time, partly offset by cost of cycle refinements.

Operating cost adjustments would be: reactor, owing to operating and administrative experience and prorating of personnel to more units (fuel costs are considered same as Case I); power plant, owing to larger plant.

Economic Aspects of Power-Production-Only, Sodium-Cooled Fast Reactor

	Cost (millions of dollars)†*				
	A	*Case I*	*Case II*	*Case III*	*B*
REACTOR AND POWER-PLANT CAPITAL					
Site and yard improvement	2.8	2.8	2.8	1.1	0.5
Reactor plant	33.1	33.1	33.1	16.6	
Power plant	15.1	15.1	15.1	12.1	13.5
TOTAL CAPITAL	51.0	51.0	51.0	29.8	14.0
ANNUAL CAPITAL COSTS					
Site and yard improvement	0.36	0.36		0.15	
Reactor plant	4.50	4.50		2.26	
Power plant	2.05	2.05		1.65	
TOTAL FIXED CHARGES	6.91	6.91		4.06	1.90
		(6.8)		(3.6)	(2.9)
ANNUAL OPERATING COSTS					
Reactor operation and maintenance	1.06	0.74	0.74	0.37	
Power-plant operation and maintenance	0.46	0.46	0.46	0.35	
TOTAL OPERATING COST	1.52	1.20	1.20	0.72	0.40
		(1.2)	(1.2)	(0.6)	(0.6)
ANNUAL FUEL COSTS					
Fuel (incl. inventory) and chemical processing	10.38	4.60	2.50	1.50	1.67
TOTAL FUEL COST		(4.5)	(2.4)	(1.3)	(2.5)
COST OF POWER					
Total annual costs	18.81	12.71	3.70	6.28	4.00
Net capacity, megawatts	145.0	145.0	145.0	160.0	100.0
Net output, million kwh	1,020.	1,020.	1,020.	1,120.	667.
Cost, mills/kwh		(12.5)	(3.6)	(5.5)	(6.0)

*A, operation of the dual-purpose reactor as currently conceived for power and plutonium. Case I, operation of the dual-purpose reactor as currently conceived for power only. Case II, operation of the dual-purpose reactor as currently conceived for power only after a 5-year amortization. Case III, future improved reactor built for power only. B, conventional steam power plant.

† Figures in parentheses are the costs computed in mills per kilowatt-hour.

Recommendations

As a result of these studies it is recommended that:

1. The development and design of a liquid-metal-cooled fast breeder with solid fuel elements be undertaken promptly.

2. On completion of this design, construction be started unless the development of other types, such as the liquid-fuel reactor, has made the plans obsolescent.

3. Concurrently with preparation of the aforementioned designs, the Commission should continue the aggressive development of a liquid-fuel breeder reactor so that it can be programmed for commercial construction and operation as early as practicable, provided development and studies indicate and confirm that this type of reactor has a definite promise of being more economic than other types of reactors.

Dow Chemical—Detroit Edison

IT HAS BEEN DECIDED to concentrate on a liquid-metal-cooled fast breeder reactor which will provide the high coolant temperature necessary for efficient power recovery. In the design for initial investigation, ideal fuel mobility will be compromised by the use of solid fuel elements of a uranium alloy. With the solid-fuel elements, the aim will be simplified fabrication and ready adaptability to the metallurgical processing. It is planned to use uranium (in some form of metallic uranium or uranium alloys to simplify processing requirements) in the breeder blanket to produce plutonium.

A design embodying the foregoing features is being undertaken on a preliminary basis. Concurrently with the work of the companies, the AEC is starting research and development work on the project.

SPECIFICATIONS FOR ECONOMICAL NUCLEAR POWER

Our conclusions as to the most important specifications for an economical power reactor are as follows:

1. The reactor should utilize low-cost fuel, i.e., it should be a breeder reactor which within itself converts thorium or depleted uranium to fissionable material for fuel.

2. The reactor should have a high breeding gain, e.g., be a fast-neutron reactor, to produce an excess of fissionable materials above its own fuel requirements.

3. The reactor should be a high-temperature machine if it is to produce power as well as fissionable materials. There appear to be possibilities of reaching the range of 950 to 1,100° F in the reactor core.

4. The reactor should be of such design as to permit integration with a variation of extraction processes under study at Ames and Brookhaven, permitting fast low-cost processing and recovery of fissionable materials and fission products.

5. The reactor should require a minimum exclusion area. An improvement could be made by continuous removal and segregation of the fission products. The separations processes mentioned above indicate promise in this direction.

6. The reactor should use uncanned fuel, preferably mobile or fluid fuel.

7. The reactor should be inherently self-regulating.

Operating Temperatures

The companies were originally most interested in reactors of known technology. It was assumed that the reactor for most immediate construction must be a thermal-neutron-energy reactor to convert U^{238} to plutonium. It would burn natural or partially depleted uranium and would use graphite or heavy water as a moderator.

A materials-producing reactor of these known types with power-producing capabilities can be built now. However, it would be operated for maximum materials production, because of the greater value of the materials, until a reduced demand for weapons material makes the power potential a more important source of return. This condition is somewhat modified for a circulating-fuel reactor, such as described by Dow-Edison reports, but the general premise still seems applicable.

Breeding

A commercial future for atomic power appears to be dependent on the development of breeder reactors. Our definition of a breeder reactor is a machine which produces more fissionable material than it burns.

At the present time nuclear power is handicapped by high capital costs, high processing costs, and significant fuel costs. If breeding is feasible, higher costs associated with nuclear power may be compensated for by the sale of surplus fissionable material as fuel.

It is necessary to assume that enough fissionable material will be available for the first charge of such a reactor and that there is a market for the fissionable material produced. The market should exist at one price level as set by the demand for weapons and eventually at a lower level as set by the demand for fuel for additional stationary and mobile power plants. Any credit for fissionable material should be at the lower level.

Low-Cost Processing

The desirability of a reduction in chemical-processing and fuel costs indicates the need for a fluid fuel and a closer integration of the reactor and the separations and decontamination processes. The expense of fixed fuel elements, limitations set by them, difficulties of charging and discharging them, aqueous separations process, and the excessive waste volumes are large factors in nuclear economics.

We have concluded that the chances are excellent that molten-metal processes can be developed into a superior separations method. If so, it should be more compatible with present reactors and a great deal less expensive than the aqueous processes, particularly if machining and jacketing of the fuel slugs can be avoided.

Mobile or Fluid Fuels

As to fuel form, it is our belief that the fuel must be mobile to facilitate frequent and rapid processing. Furthermore, a closely integrated processing system must be provided for the recovery of pure plutonium and the removal of hot fission products, specifically, the metallurgical processing system mentioned above. A natural corollary of these two requirements is that the most desirable fuel is one that can be maintained in the liquid state at all times. If it is found necessary to use a solid fuel, then the fuel elements must be of such form or shape that they may be fabricated simply enough to make a fabrication process by remote control feasible. Fuel elements which can be cast from the molten metal should satisfy this requirement.

We have surveyed the fluid-fuel possibilities for a fast reactor. The information which has been at our disposal indicates several possible cate-

gories of fluid fuels, each of which has distinct disadvantages and difficulties in operation: (1) eutectics of uranium or of plutonium with melting points of approximately 500° C and higher; (2) slurries such as the dispersion of certain intermetallic compounds or alloys of uranium in low melting point alloys; (3) fused salts. All of these possibilities introduce serious development problems dealing with containers, radiation stability, reprocessing, etc.

It is believed that progress will ultimately be made in developing techniques for using them in the temperature ranges required, or in lowering the melting points further. Much development work is required on any of the fluid-fuel systems as well as on a reactor design in order to make use of them. To select a reactor which can be built in a reasonable time, it seems preferable to use the fuel in a solid form.

Assuming this to be necessary, some of the advantages of the fluid fuels can be gained through the use of relatively low-melting materials even though they are used in the solid form. Within a large group of possible materials, a uranium alloy is a reasonable choice for the initial effort.

REACTOR TYPES THAT MEET REQUIREMENTS

A number of mechanical design types, specified in the table on this page, are conceivable which might meet all or part of the desired requirements. Some possible designs are:

1. A jet-mixed centrifugally separated liquid-cooled reactor with liquid fuel and continuous reprocessing (type C).

2. A reactor having liquid fuel contained in a "reactor pot" with the coolant in tubes (type A-1).

3. Coolant outside fuel tubes with liquid or mobile fuel inside tubes, with or without the fast, continuous reprocessing.

The figures given in the table are, at best, reasonable approximations, but they provide a basis for a relative comparison of the configurations considered. In each case, slightly different configurations might give improved performance for the same basic concept. The design which will be investigated initially, the use of a uranium alloy as a fuel in a solid form, is the general type of configuration under column B in this table.

A basically simple mobile-fuel reactor type is one in which a pot of molten fuel is cooled by coolant flowing in tubes or metal shells through it. The container-material problem is critical in this case, with a material of relatively high thermal conductivity required to contain liquid-metal fuel.

Types A-1, A-2, and A-3 are variations of this basic idea and are calculated for varying potential fuel compositions and fuel-element dimensions.

To alleviate the materials requirement somewhat, it should be possible to flow fuel in and out of the pot in the molten state but hold it in the solid state at a somewhat lower temperature during the major portion of the time in the reactor. This is the possibility envisioned in type B.

Limiting factor of the specific power output of the types A-2, B, and C reactors is the product of density and specific heat of the coolant (0.24 cal/cm³/° C for sodium). For types A-1 and A-3, the high heat release per unit volume in fuel requires extremely small fuel elements or large temperature drops. The maximum coolant temperature for all types is limited by corrosion effects.

Possible Reactor Configurations for Economic Power

Description	*A-1 (Radiator; liquid fuel, liquid coolant)*	*A-2 (Radiator; slurry fuel, liquid coolant)*	*A-3 (Radiator; liquid fuel, solid fertile material, liquid coolant)*	*B (Radiator; solid fuel, liquid coolant)*	*C (Liquid-liquid; liquid-fuel, liquid coolant, pot)*
Max. heat output (kw)	25,000	460,000	75,000	450,000	220,000
Max. coolant temperature available for steam generation (° F)	900	1,020	900	1,020	930
Electrical power output at 30% efficiency (kw)	7,500	138,000	22,500	135,000	66,000
Coolant Material	Na	Na	Na	Na	Na
Max. circulating velocity (ft/sec)	30	30	10(30)	30	30
Max. temperature (° C)	480(610)	480	480	550	500
Min. temperature (° C)	350	350	340	270	200

Ultimate Reactor Type

The theoretical reactor that would incorporate all the most desirable ultimate objectives is a fast breeder with a true fluid fuel (type C in the table). It would include metallurgical processing and would not have conventional heat-transfer surfaces. It might be built of refractory materials that would be reasonably good for either thermal- or high-energy neutrons.

The core of the reactor would be all molten metal.

The fertile material might be either depleted uranium or thorium, depending on the product desired. One primary consideration would be safety. For example, on board a ship or in a congested area, thorium would probably be the fertile material and U^{233} or U^{235} would probably be the fissionable material. This, with frequent purification of the fuel metal, would keep the toxic and radiation hazards to a minimum within the reactor and any one storage place for waste. Where adequate protection is provided, a depleted- or natural-uranium breeder blanket would be used on the outside of the fast-reactor core to produce plutonium.

In other possible configurations the fluid fuel might be circulated for cooling completely outside the core with more extensive external circuits. However, such systems are not considered here, primarily because of the inventory of fissionable material required in the external circuit.

Monsanto Chemical—Union Electric

THE LIMITATION in this study that the plutonium-power reactor must be built in the next few years means that the design must be based on reasonably proven components and data already accumulated by AEC.

The studies presented here are based on operation of the reactor for production of military plutonium for an assumed period of five years, and include reactors that conceivably could be built in from four to six years.

The expected life of a power plant is usually 20 to 35 years. Therefore, consideration must be given to the eventual production of power alone when the military plutonium market no longer exists, or to the amortization of the power-plant investment within the period of the military Pu market.

At the beginning of the study, natural-uranium reactors were considered. However, later indications by the AEC that enriched uranium would be made available provided wider latitude in the types of reactors to be investigated.

The need for early design and construction led first to the investigation of any reactor having a large power output about which the maximum of design, cost, and operating data were available. The Hanford reactors fulfilled all these specifications.

Sodium or the sodium-potassium eutectic appeared to be the most promising of the potential high-temperature coolants because of the large amount of data available from both commercial handling of sodium and corrosion studies made at several AEC installations.

The sodium-potassium eutectic offered the advantage over sodium of a lower melting point and hence a lower possible inlet temperature with a higher possible heat pickup, but the presence of potassium offered such disadvantages (the possibility of severe interaction between the potassium and the graphite, and a higher absorption cross section) that pure sodium was chosen.

Further study indicated that the very high film heat-transfer coefficient, the greater permissible temperature rise of the coolant without involving pressure, and the lack of corrosion of stainless steel by sodium up to temperatures of at least 900° F would make it possible to remove larger amounts of heat from the fuel elements with sodium than could be removed with water, whether pressurized or not.

Since the plutonium production is nearly proportional to the heat output of a reactor, other things being equal, the use of sodium gives the important advantage of a higher plutonium production rate for a given size reactor. The value of plutonium is so great as compared with electric power that it becomes necessary to maximize plutonium production. With sodium as a coolant, the temperatures which maximize plutonium production are high enough to permit the practical generation of electric power. This does not appear to be the case with water as the coolant.

FIRST-CHOICE OF POSSIBLE REACTOR TYPES

Metallic uranium was chosen for the fuel to minimize the enrichment required and because of the large amount of information available on this material. On the basis of our information, an unalloyed metallic-uranium fuel element should be limited in top temperature by the changes which occur at the α-β phase transition (665° C, 1,229° F). To give some margin of safety, we chose 1,100° F as the maximum uranium temperature. The fuel-element design was based on the general assumption that this results in the minimum plutonium cost.

On a comparable basis, and with the uranium-metal temperature as the limiting factor, an internally-cooled fuel element permits greater heat output than an externally-cooled one. Obviously, a fuel element which is both internally and externally cooled would result in still greater heat output than would a fuel element that is only internally cooled.

Two potential designs were arrived at, both having the same general arrangement but differing in the coolant system, with resulting variations in the loading and unloading techniques.

The moderator and surrounding 2-ft-thick reflector would be assembled from graphite blocks to form an octagonal prism 24 ft high by 39 ft across the face. This prism would be provided with cooling channel holes spaced on a square lattice. The tubular fuel elements, placed in these holes by a suitable loading mechanism, would be cooled by sodium flowing both through the fuel elements and the annular space between the walls of the cooling channel and the fuel elements.

The hot sodium would flow through a heat exchanger, and then be pumped back to the reactor. Special means would be provided to prevent the sodium vapor from diffusing into the graphite, to detect sodium leaks, and to cool the graphite.

The whole arrangement of the core and sodium pools would be surrounded by thermal insulation and a suitable water-cooled shield, such as massive concrete or a mixture of hydrogenous and heavy materials. The upper section of this shielding would be provided with ports or locks as required, permitting the introduction or removal of fuel elements or cooling-channel tubes. These ports or locks would be suitably plugged by removable sections made of metal and hydrogenous material locked into place.

The fuel elements, suitably encased, would be maintained in a central position in the cooling channel by special positioning devices which would not interfere with the flow of coolant.

Provisions are made in both of the designs for retubing the reactor if required. This would be a difficult operation, but since tubing failures are not expected very often, this seems to be a tolerable situation.

Since full-load operation will require relatively frequent replacement of fuel-element assemblies, the design of the reactor is such that the fuel channels can be loaded and unloaded while operating at full load.

Nuclear Characteristics

The most economical plutonium-power reactor seems to be one using enriched fuel. The cost of enriching is more than offset by the reduced unit cost of the plutonium produced be-

cause, in general, enrichment results in a higher allowable specific power, a longer permissable irradiation of the fuel, and higher plutonium concentration in the output uranium.

Thus there would be realized not only a greater plutonium production per year but also a saving in fuel and operating costs (from the longer irradiation period) despite the increase in the cost of fuel due to enriching. In addition, the unit cost of the separated plutonium would be still further reduced because the higher plutonium concentration in the irradiated uranium would reduce chemical-processing costs. The full benefits of enriched fuel have not been realized in our studies as yet. Variation of lattice spacing and some other parameters have to be explored.

Although the main advantages of internal cooling are those based upon heat-transfer characteristics which result in higher power per unit cell, it is possible, by this method, to gain some advantage in criticality.

Two methods have been considered for increasing the U^{235} content of the average cell. One is a small uniform enrichment of all the fuel used in the reactor, and the other is a "spiking" technique employing more highly enriched or pure U^{235} in a given fraction of the channels.

Heat Exchanger

To prevent contact between sodium and water, the heat exchanger would be a shell-and-tube type with double concentric tubes to provide a barrier space between the two mediums. The barrier or leakage space would be filled with mercury for good heat transfer. About 15 electromagnetic pumps will be used to handle the sodium flow.

Conversion of Heat to Electricity

Internal cooling. The power cycle for the reactor with internal cooling is based on receiving sodium from the reactor at 650° F and returning it at 300° F. The hot sodium from the reactor flows through the heat exchangers to produce turbine throttle steam at 150 psia, dry and saturated. Steam is generated at a rate of 3-million lb/hr and is fed to a turbine cycle with a gross thermal efficiency of approximately 22%.

The resulting electric output is about 220,000 kw from two turbogenerator units of 110,000 kw each. Auxiliary power for pumping cooling water, condensate, and sodium totals approximately 5.5% of the gross capability.

Characteristics of Na-Cooled Graphite Reactors

Purpose	Pu and power
Neutron energy	Thermal
Power (heat Mw)	1,000 (3,000)*
U^{235} enrichment (%)	0.83 (0.95)*
Fuel elements	Internally cooled tubes (and externally cooled tubes)*
Moderator	Graphite
Reflector	Graphite
Shield	Concrete
Primary coolant	Na
Fertile material	U^{238}
Max. uranium temp. (° F)	1,100
Coolant	
Inlet temp. (° F)	300
Outlet temp. (° F)	650 (900)*
Max. velocity (ft/sec)	20
Gal/min at 300° F	70,000 (120,000)*
Pumping power (50% efficiency) (kw)	3,000 (5,000)*
Core	Octagonal prism, 20 ft high, 35 ft across flats
Reflector thickness (ft)	2
Shield thickness	Not yet specified
Over-all dimensions	Not yet specified

* Figures in parentheses are changes that would be made in characteristics for a 3,000-Mw reactor.

Internal and external cooling. Two power cycles have been considered for the reactor with both internal and external cooling. One utilizes the heat output of the sodium coolant over the entire temperature range between the reactor inlet and outlet temperature (300 to 900° F), and the other rejects the heat of the coolant below 500° F directly to the heat sink.

The main advantages of the latter cycle are a substantially reduced total investment and a power output of more readily marketable size.

The steam conditions for both power cycles have been taken as 400 psia, at 746° F to the turbine and 1.5 in. Hg absolute pressure at the condenser. In the first cycle, steam would be generated at a rate of approximately 8.8-million lb/hr and would be fed to a turbine cycle with a gross thermal efficiency of approximately 28%. The resulting gross electric output would be about 878,000 kw from five turbogenerator units.

Auxiliary power for this power cycle, including the pumping of sodium, would amount to approximately 5% of the gross capability.

In the second cycle, steam would be generated at the rate of approximately 4.8-million lb/hr with the same cycle efficiency as in the first cycle. The resulting gross electric output would be about 579,000 kw from three turbogenerator units. Allowing for auxiliary power and sodium pumping, the net output would be about 554,000 kw. The heat from the coolant in the temperature range of 300 to 500° F would be rejected by producing steam at 25 psia and condensing it at 20 psia in a water-cooled heat exchanger.

Conversion to Power Only

The studies presented here are based on a reactor producing plutonium for a period of five years. The power plant should be amortized over the same period of time unless there is some way of making it useful after this period.

Subsequent to the five-year period there would be the problem of choosing one of several courses for continued power production during an era in which power is the controlling factor. Assuming that nuclear fuel would continue to be available, the first alternate would be to continue operating the reactor as a heat source for the production of steam-generated electricity. It would no longer be necessary to refuel as often, and operating costs would be reduced somewhat; however, the cost of electricity from such a source might be about as high as that from conventional fuel-burning plants even though the equipment were fully amortized.

There are two other alternatives, both of which involve shutting down the reactor. In one of these, a modern high-pressure boiler and a high-pressure topping unit would be installed. In the other, only a high-pressure boiler would be built to supply the turbogenerator. In this case it is assumed, of course, that the original plant would have been designed to produce steam at some high pressure where the cycle efficiency can later be improved through the use of superheat to compete with modern coal-burning plants. This probably means dumping a certain amount of heat from the reactor to produce high-pressure steam. In both these alternatives, the original plant

would have been designed for economical change-over after the plutonium-production period.

Pu-Power Plant Economics

The table on this page shows the production costs of electric power for the two cases discussed. Capital costs in this table were derived from preliminary information furnished by Westinghouse Electric Corp. and Union Electric Co. The figures do not include such items as cost of land, financing charges, public liability insurance, federal income taxes, and profit, which would have to be added to arrive at an ultimate selling price.

In a reactor producing plutonium and power, the cost of the heat should be borne by the plutonium since it is an inevitable consequence of the formation of this material. The actual heat in the steam (but not necessarily the equipment, operation, and other costs for transferring it) can be considered free. It might be expected that cost of electrical power made from a free heat source would be less than that from conventional sources, and the difference could be used to reduce the cost of plutonium. However, from the table it will be seen that the cost of electric power from a reactor is very close to that from a modern coal-burning plant. It turns out that it costs more to absorb heat by making steam suitable for a turbogenerator than to dump the heat into a river. More important, the short amortization period of five years assigned to the reactor and power plant raises the depreciation charges to the point where, together with the other cost increases, the savings in fuel are approximately offset.

The selection of a five-year depreciation period was somewhat arbitrary but was based on the assumption that military plutonium may not be required after the design, construction, and five-year operation of a plutonium-power plant. Moreover, "certificates of necessity" are issued for defense plants, and this plutonium-producing reactor certainly comes in this category. If military plutonium were required for periods longer than five years, it is obvious that electric power could be sold cheaper or the profit from its sale at prices competitive with coal-generated electricity could be used to reduce the cost of plutonium slightly.

PROBLEMS THAT REQUIRE DEVELOPMENTAL STUDY

Even though the start of this study considered the reactor to be a sodium-cooled Hanford-type, and its selection was on the basis of a great deal of applicable practical and research information, there are design changes and problems which require research and developmental study.

First are problems that must be solved for the reactor to operate and have a reasonable life expectancy. Without their solution, it is not prudent to design a nuclear reactor system.

1. What is the reaction between sodium and graphite under the temperature, radiation, stress, and other condition in the proposed reactor?
2. What are the possible graphite temperatures?
3. Will there be carburization and embrittlement of the thin cooling-channel tubes?
4. Will cooling be necessary to prevent carburization of the control-rod thimbles?

There are a number of problems that must be solved before final design is undertaken. They are:

1. Feasibility of constructing fuel assemblies must be proved; testing procedures would have to be developed.
2. What are corrosion and erosion effects of the sodium on the element jackets under in-pile conditions?
3. What are radiation damage effects on materials of construction, components, and mechanisms?
4. Mechanisms for refueling and retubing at operating temperatures with sodium present must be developed and tested under operating conditions.
5. Refueling techniques and the effect on reactor control of unloading and refueling during operation will require testing.
6. Effect of sodium on construction materials and on platings for uranium and the durability of uranium platings under operating conditions must be investigated.

There are also problems that must be solved before final construction and operation. These problems are:

1. Work must be done on decontamination and repair or replacement of components.
2. Suitable sodium pumps and containers for shipping fuel elements to processing plants must be developed.
3. Problems of analyzing and removing impurities from the sodium, and the monitoring and purification of the circulating helium, need further study.
4. Design and construction of a reactor stimulator would increase the knowledge of the time and temperature relations of the reactor.
5. Design limits should be set for heat output of any fuel channel to determine a suitable safety factor. This problem is affected by such variables as warping and distortion of fuel assemblies, power surges, and fouling of heat-transfer surfaces. —END

Electric-Power Costs*

	Internally cooled		*Internally and externally cooled*		*Modern coal-fired plant*	
Capital costs (10^6)	26		61		44	
Net output (kw)	210,000		554,000†		260,000	
Cost ($/kw)	124		110		169	
	(10^6/yr)	*(mills/kwh)*	*(10^6/yr)*	*(mills/kwh)*	*(10^6/yr)*	*(mills/kwh)*
Depreciation‡	5.20	3.30	12.20	2.94	1.26	0.65
Property taxes, insurance	0.52	0.33	1.22	0.29	0.88	0.45
Fuel cost (coal, $0.23 per 10^6 BTU)	0.0	0.0	0.0	0.0	4.63	2.37
Operating cost	0.79	0.50	2.10	0.50	0.98	0.50
TOTAL	6.51	4.13	15.54	3.73	7.75	3.97

* Assumptions: Plutonium sale offsets all fuel costs, operating time, 7,500 hr/yr; taxes and insurance, 2%; and depreciation, 20%.
† Heat rejected below 500° F. ‡ 20% for reactors, 2.86% for coal-burning plant.

SUPPLEMENT TO

Nuclear Reactor Catalog

The concise tabulation of declassified details of reactors in operation or in advanced stages of design and construction is brought up to date

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WITHIN THE past year several new reactors have been announced and further details on existing reactors have been published. The purpose of this paper is to present a supplement to the "Nuclear Reactor Catalog" which appeared in NUCLEONICS last year (*1*).

The listings follow the same style as used in the original catalog. For example, the classification of a reactor covers the following points of interest: neutron chain reaction based primarily on thermal, intermediate, or fast neutrons; fuel-moderator assembly, either homogeneous or heterogeneous; moderator; purpose of reactor; power level (not to be interpreted as the generation of electrical power, but as the rate of heat generated); and neutron flux in $n/cm^2/sec$ (thermal, unless otherwise noted, usually designating the maximum).

The information listed supersedes the information given in the first list (*1*) in the case of reactors that appear in both lists. All information in the first list that still applies to reactors listed here is repeated in full, with changes or additions made to include the latest data.

Clementine, the Los Alamos Fast Reactor, which was listed in the original catalog is on longer usable and is being dismantled.

In addition to the listings here, a number of foreign countries have expressed interest in the construction of reactors (*2*).

In Great Britain, a low-power breeder reactor, to be called ZEPHYR, is under construction at Harwell. Design and feasibility studies are under way there for a slow-neutron, enriched-uranium power reactor (prototype for ship propulsion) and for a slow-neutron, natural-uranium reactor for the generation of electricity (*2, 3*).

Groups Interested in Research Reactors

Alabama Polytechnic Institute
University of California at Los Angeles
Case Institute of Technology
University of Michigan
Pennsylvania State College
University of Utah
University of Texas
Naval Research Laboratory
Watertown Arsenal

A 10,000-kw reactor for ship propulsion is being planned by a group from the Netherlands and Norway (*4*).

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Table on next page→

Available Data on Nuclear Reactors

Name	*Classification*	*Fuel*	*Fuel Core*	*Reflector*
Reactors in Operation				
Bulk Shielding Facility (Swimming Pool) (Oak Ridge National Laboratory, Oak Ridge, Tenn.) (*6*)	Thermal Heterogeneous Light water Research 100 kw	Plates of enriched U (>90% U^{235}) containing 30 to 40 gm of U^{235} encased in Al alloy sandwiches. Fuel element is an assembly of 5 parallel plates, ~3 in. wide, 0.1 in. thick, 24 in. long, spaced ~½ in. apart. Al to H_2O ratio is 0.3. Fuel elements held in a grid 5 in. deep	Critical mass ~3 kg of U^{235} in fuel core 12 × 12 × 24 in.; with allowances for other factors including beam holes, burn-up, 3.5 kg; with BeO reflector, 2.4 kg in a fuel core 9 × 12 × 24 in.	10 cm of BeO on 4 sides of active lattice; or light water
EBR, Experimental Breeder Reactor (Reactor Testing Station, Arco, Idaho) (*7*)	Fast Heterogeneous Research and breeding 6.5×10^{14} n/in.^{2}/sec	U^{235}	Core about size of football, surrounded by blanket of natural U	
MTR, Materials Testing Reactor (Reactor Testing Station, Arco, Idaho) (*8*)	Thermal Heterogeneous Light water Research $>4 \times 10^{12}$	Similar to Bulk Shielding Facility		
LITR, Low-Intensity Test Reactor (Oak Ridge National Laboratory, Oak Ridge, Tennessee) (*9*)	Thermal Heterogeneous Light water Research			
SUPO, Super Power Water Boiler (Los Alamos, New Mexico) (*10*)	Thermal Homogeneous Light water Research 45 kw 1.7×10^{12}	Enriched uranium nitrate solution containing 88.7% of U as U^{235}; 777 gm of U^{235} for critical mass; 870 gm U^{235} used; solution density 1.10; 12,700 cm^3 solution	Solution contained in a 12-in. dia. stainless-steel sphere	About a 55-in. cube of graphite
North American Water Boiler (North American Aviation, Inc., Downey, Calif.) (*11*)	Thermal Homogeneous Light water Research	1.5 lb of uranium fuel in form of U^{235} enriched uranyl nitrate in light-water solution.	Solution contained in a 1-ft dia. stainless steel sphere, $\frac{1}{16}$ in. thick	Graphite, 5-ft dia. and 6-ft high
ZOE (Chatillon, France) (*12*)	Thermal Heterogeneous Heavy water Research 5 kw $2\text{-}3 \times 10^{10}$	UO_2 in tablets 3 cm high stacked in Al tubes of 66 mm I.D., and 180 cm effective height. Effective density of oxide is 8.3	Heavy-water moderator (at 40 ± 6° C) contained in cylindrical Al vat, 181 cm I.D., 235.5 cm high. Maximum number of fuel bars is 69 (3.55 tons UO_2), set hexagonally (sides of hexagon 18.6 cm)	Graphite blocks (diffusion length, 45 cm). 15 cm of heavy-water at bottom
P-2 (Saclay, France) (*2*)	Thermal Heterogeneous Heavy water Research 1,500 kw	Uranium rods		

Shielding	*Over-all size*	*Control*	*Coolant*	*Remarks*	*Name*
16½ ft of water above, and 3½ ft plus concrete below		2 B-Pb shim-safety rods (mixture of Pb and boral in oval Al can 1 × 2½ in. × 26 in. long). 1 control rod, same dimensions	Light water (convective flow)	Negative temperature coefficient 0.0075%/°F. Maximum available slow-neutron flux, 10^{12} n/cm²/sec, maximum available epithermal flux, 3×10^{12} n/cm²/sec.	**Bulk Shielding Facility (Swimming Pool)** (Oak Ridge National Laboratory, Oak Ridge, Tenn.) *(6)*
			NaK. Exit temperature 660° F	Steam generated at 400 psi from secondary NaK coolant stream and fed to a 250-kw turbogenerator. Power density, 4.0 kw/in.³	**EBR,** Experimental Breeder Reactor (Reactor Testing Station, Arco, Idaho) *(7)*
			Light water	For study of materials exposed to intense radiations	**MTR,** Materials Testing Reactor (Reactor Testing Station, Arco, Idaho) *(8)*
				Served as mock-up for MTR and now used for research. MTR fuel elements used	**LITR,** Low-Intensity Test Reactor (Oak Ridge National Laboratory, Oak Ridge, Tennessee) *(9)*
½ in. of B_4C + paraffin; 2 in. steel; 4 in. lead; 5 ft concrete		Two additional control rods (see HYPO) move into reactor core in re-entrant thimbles	Light water circulated through three 20-ft long, ¼ in. O.D., 3/16 in. I.D. stainless-steel cooling tubes	Estimated max. intermediate flux 2.8×10^{12}, est. max. fast flux 1.9×10^{12}. Unit in air circulation (100 l/min) system recombines H_2 and O_2 to keep H_2 concentration below detonation limits	**SUPO,** Super Power Water Boiler (Los Alamos, New Mexico) *(10)*
2 ft of concrete blocks					**North American Water Boiler** (North American Aviation, Inc., Downey, Calif.) *(11)*
Concrete walls 150 cm thick		Two sets of two types of Cd safety rods. Cd regulating bars		Laplacian = 5.8 m^{-2}	**ZOE** (Chatillon, France) *(12)*
			Nitrogen at 10 atm	400 kw per ton of uranium	**P-2** (Saclay, France) *(2)*

Continued

Reactors in Operation (Continued)

Name	*Classification*	*Fuel*	*Fuel Core*	*Reflector*
BEPO, British Experimental Pile (Harwell, England) *(2)*	Thermal Heterogeneous Graphite Research 4 Mw 10^{12}	0.9-in.-dia, 12-in.-long uranium bars, encased in Al; 28 tons for criticality, 40 tons for full load, central 900 channels used; 20 bars per channel, $7\frac{1}{4}$ in. between channels	Right cylinder, 10 ft radius, 20 ft long	About 3 ft of graphite
JEEP (Kjeller, Norway) *(2)*	Thermal Heterogeneous Heavy water Research 300 kw 10^{12}	2.200-kg uranium slugs in Al tubes; 35.5 kg per rod; rods 25.4 mm dia, 300 mm long, placed on 180-mm centers	1.9 m long; 7 tons of heavy water moderator in 2-m-dia. tank	Graphite 700 mm thick
HRE, Homogeneous Reactor Experiment (Oak Ridge National Laboratory, Oak Ridge, Tennessee) *(14)*	Homogeneous 1,000 kw	Liquid solution of fuel and moderator		
CP-3', Argonne Heavy Water Reactor (Argonne National Laboratory, Chicago) *(15)*	Thermal Heterogeneous Heavy water Research	Uranium		
TTR, Low-Power Thermal Test Reactor (Knolls Atomic Power Laboratory, Schenectady, N. Y.) *(16)*	Thermal Heterogeneous Research 100 watts 3.4×10^9	2.7 kg U^{235} required for criticality; extra 0.1 kg provides about 0.6% excess reactivity	20 fuel slug tubes, each 2 in. dia., 24 in. long, containing U-Al alloy disks with polyethylene spacers strung on $\frac{3}{16}$-in.-dia. rod; disks (slugs) immersed in light paraffin base oil contained in a slug tube. Tubes in cylindrical array in an Al tank of 12-in. I.D. and 18-in. O.D.; tank filled with water	30-in. cylindrical ring of graphite

Reactors in Advanced Stages of Design or Construction

Raleigh (North Carolina State College, Raleigh, N. C.) *(17)*	Thermal Homogeneous Light water Research 10 kw 5×10^{11}	14 liters of light water solution of UO_2SO_4 containing 790 gm U^{235} of 90% isotopic enrichment. Density of solution = 1.08 gm/cm³	Reactor solution contained in stainless-steel cylinder $\frac{1}{16}$ in. thick, 11 in. high, $10\frac{3}{4}$ in. dia.	20 in. graphite; 105 ft³, 5.4 tons. ρ = 1.65 gm/cm³
STR, Submarine Thermal Reactor (Reactor Testing Station, Arco, Idaho) *(8)*	Thermal Ship propulsion			
SIR, Submarine Intermediate Reactor (Knolls Atomic Power Laboratory, Schenectady, N. Y.) *(8)*	Intermediate Ship propulsion			
Ship	Propulsion			

Shielding	*Over-all size*	*Control*	*Coolant*	*Remarks*	*Name*
6-in. cast iron plate, and 6-ft concrete on sides and $7\frac{1}{2}$ in. on top; 600 tons steel, 3,000 tons concrete		4 horizontal and 10 vertical boron-carbide filled hollow steel rods, 2 in. dia.	Air; single pass, 180,000 ft^3/min. Cross-section of each empty channel is $3\frac{1}{2}$ in^2.	Maximum surface temperature 200° C. Uranium cartridges improved so power output is 6 Mw. Also see ref. *13*	**BEPO,** British Experimental Pile (Harwell, England) (*2*)
Octagonal concrete shield, 2 m thick on sides		4 cadmium plates 1,300 mm long, 350 mm wide, 1.7 mm thick, held between Al plates	4 liters of heavy water per sec (inlet 20° C, outlet 40° C)		**JEEP** (Kjeller, Norway) (*2*)
			Heat removed by pumping fuel solution through external heat exchanger	Has operated at full design power and has generated about 150 kw of electric power	**HRE,** Homogeneous Reactor Experiment (Oak Ridge National Laboratory, Oak Ridge, Tennessee) (*14*)
				Improved design of CP-3	**CP-3′,** Argonne Heavy Water Reactor (Argonne National Laboratory, Chicago) (*15*)
Reactor located in a room with 6-ft-thick concrete walls		Coarse: 6 Fe-clad Cd sheets, 4 in. wide, 18 in. long, at periphery of tank. Fine: 2 Cd rods, 18 in. long, $\frac{1}{2}$ in. dia., move between fuel slug tubes. Safety: four $\frac{1}{2}$-in.-dia. Cd rods		Internal thermal column is a graphite cylinder, 12 in. dia., 18 in. high. Test hole is in center of column. Temperature change of 10^{-3}° C causes reactivity change of $\Delta k/k = 10^{-7}$. (Negative temperature coefficient)	**TTR,** Low-Power Thermal Test Reactor (Knolls Atomic Power Laboratory, Schenectady, N. Y.) (*16*)
6 ft. of concrete. Barytes ore as coarse aggregate, and colemanite ore as fine aggregate. $\rho = 3.4$ gm/cm^3	Octagon, 17 ft across, $9\frac{1}{2}$ ft high	2 control rods (S.S. tubes of 2.5-gm/cm^3 sintered B_4C powder, in reentrant sheaths). 2 shim rods (4-in.-wide Cd strips, periphery of reactor cylinder)	Light water (refrigerated, city water) 1 gal/min flow through each of 4 helical coils of $\frac{1}{4}$-in. S.S. tubing, 7 ft immersion length (total immersion length 28 ft)	Expected negative temperature coefficient 0.7 gm U^{235}/° C at low temperatures and 1.25 gm U^{235}/° C at high temperatures (taken to be same as Los Alamos Water Boiler). Maximum reactor solution temperature 80° C	**Raleigh** (North Carolina State College, Raleigh, N. C.) (*17*)
			Light water	Land-based prototype	**STR,** Submarine Thermal Reactor (Reactor Testing Station, Arco, Idaho), (*8*)
			Liquid sodium	Land-based prototype at West Milton, N. Y.	**SIR,** Submarine Intermediate Reactor (Knolls Atomic Power Laboratory, Schenectady, N. Y.) (*8*)
				Contracts have been let for work on propulsion reactors for large naval vessels	**Ship**

Gamma-Ray Output of Radium

To provide a more precise standard γ-ray source, the authors made cavity-chamber measurements of radium γ-ray output in 0.5-mm Pt. Their value of 8.44 ± 0.07 r/mg/hr at 1 cm compares well with corrected previous measurements

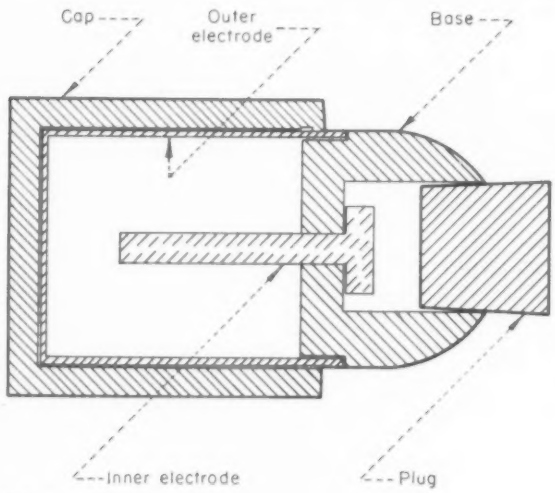

FIG. 1. Ionization chamber

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THE GROWING USE of large gamma-ray sources in medicine, industry and research has increased the importance of standard sources of accurately known output, for calibrating detecting instruments and other sources.‡ In many respects, radium is still the most convenient standard for this purpose.

The figure commonly obtained is the dose rate in roentgens at 1 cm from 1 mg of radium encased in 0.5 mm of platinum, as derived from measurements with an "air-wall" cavity chamber (thimble chamber). In 1937, Laurence (*1*) tabulated the results of the measurements made in the preceding few years; after being corrected to air-wall conditions, they ranged from 7.95 r/mg/hr at 1 cm to 8.65 r/mg/hr at 1 cm, with a mean value of 8.35. Since then, the values published have ranged from 8.0 r/mg/hr at 1 cm (*2*) to 8.47 r/mg/hr at 1 cm (*3*).

Apparatus

The chamber used here was the condenser type, first used by Sievert (*4*) (see Fig. 1). The collecting volume was 1.95 cm long by 1.60 cm in diameter, enclosed by a 0.5-mm polystyrene wall coated inside with a thin layer of graphite. The inner electrode, made of graphite, was 1.35 cm long by 0.19 cm in diameter. A polystyrene base served to support the inner electrode and to insulate it from the outer one. The wall thickness could be varied by the addition of close-fitting polystyrene caps of 0.5–15.5 mm thickness.

Radium sources. A number of different radium sources were used. All were in the form of platinum tubes of 2.5-mm outer diameter and 1.5-mm inner diameter, containing known quantities of radium salt. The tubes ranged in length from 1.0 cm for the 2-mg source to 5.6 cm for the 100-mg source. Their contents had been determined by comparison with the Canadian standard.

Apparatus set-up. During a reading, chamber and source were held by light wooden supports on a stand designed to minimize the amount of scattered radiation reaching the chamber. For source-to-chamber distances less than 100 cm, the source and chamber were located more than 2 m from the nearest walls and half way between the floor and ceiling of a room 3 m high. For greater distances, measurements were made outdoors with the chamber 2.5 m above the ground.

Operation. The rate of ionization occurring in the air volume of the chamber at a given distance from the source was determined by charging the electrodes to a potential difference of about 100 volts, exposing the chamber to the gamma-radiation from the source for a known interval of time, and measuring the resulting decrease in voltage. Voltages were measured on a Baldwin-Farmer electrometer which had been calibrated against a d-c potentiometer. (The electrometer is designed to present an extremely small capacity across the input terminals in parallel with the capacity of the chamber, so that the chamber does not lose an undue fraction of its charge.)

For the determination of the absolute gamma-ray output of radium, it was necessary to know the volume and capacitance of the chamber. The volume was calculated from the known dimensions to be 3.85 cm^3. The capacitance was 1.26×10^{-12} farads.

Measurements

Ionization measurements were made over a range of source-to-chamber dis-

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* PRESENT ADDRESS: Carleton College, Ottawa, Canada.

† PRESENT ADDRESS: General Electric Co., Nela Park, Cleveland, Ohio.

‡ The term "output" is used here to denote the dose rate (in roentgens per hour) at a specified distance from a source due to the radiation from the source. There seems to be no commonly accepted term to express this quantity.

tances between 10 and 150 cm and with a number of different source strengths. In each case, the ionization was measured for eight wall thicknesses between 0.5 and 16.0 mm in order that a curve of ionization vs wall thickness could be obtained. Each curve was measured several times with the sequence of wall thicknesses chosen at random to reduce the effects of any slow variations in such factors as temperature and pressure.

A typical curve of ionization vs wall thickness is presented in Fig. 2. It shows the familiar initial rise with increasing thickness as electron equilibrium is established, the maximum around 3 mm, and the subsequent gradual fall-off due to gamma-ray absorption. The position of the maximum depends on the distance of the chamber from the source, the intervening air acting as a substitute for the equivalent mass per unit area of wall material. Thus, at a distance of 10 cm, the maximum occurs at 3 mm of polystyrene, whereas at 150 cm it is nearer 1.5 mm.

As one would expect, the slopes of the curves between 8 and 16 mm correspond approximately to an absorption coefficient of σ_a for the attenuation of the gamma-rays in the chamber wall. The final portion of each curve was extrapolated back to zero wall thickness to get the ionization, I_0, corresponding to no attenuation. [As pointed out by Kaye and Binks (*2*), the concept of a dose rate at zero wall thickness is somewhat artificial, since in practice there must always be sufficient material between the source and the measuring volume to establish equilibrium between the gamma-rays and their secondary electrons. However, in order to compare the results of different workers it is necessary to reduce their measurements to a common wall condition, and since a variety both of wall materials and of wall thicknesses has been used in past work, the simplest procedure is to correct to zero wall thickness.] A further small correction was made for the absorption in the air between the source and the chamber; it amounted to 0.3% per meter.

Ionization values. The values of I_0 obtained for each distance and source strength, expressed in terms of the change of voltage on the chamber per minute, are given in column 3 of Table 1. Column 2 lists the effective contents, Q, of the sources used. By "effective content" is meant the true content of the source in milligrams of radium reduced by the percent absorption of the emitted gamma-rays in the radium salt; for example, a source of 25-mg effective content would have a gamma-ray output 25 times that of a single milligram having negligible absorption in the salt. True source content would be slightly greater.

In column 4, the values of the extrapolated ionization, I_0, have been divided by the effective contents to give the ionization per mg of radium. The resulting numbers should depend only on the distance of the chamber from the source. Provided the scattering from the surroundings is negligible, and provided the source-to-chamber distance may be taken to be the distance from the center of the source to the geometrical center of the chamber, the variation with distance should follow the inverse-square law.

Scattering. The effect of scattered radiation was estimated using the fact that the ratio of the scattered and primary intensities can be expressed roughly by $Kd^2(1/D^2)$, where d is the source-to-chamber distance, $1/D^2$ is the mean square value of the inverse of the distance to the surrounding objects, and K is an empirical factor between 0.05 and 0.1 (*5*). On this basis, the scattered intensity amounted to considerably less than 1% of the primary intensity for all distances used. Thus, any deviation from the inverse-square law should be due to a displacement of the effective center of the chamber from the geometrical center (as a consequence of the fact that, because of the predominantly forward ejection of Compton electrons, more of the ionization in the chamber is produced by the gamma rays interacting in the front wall than by those interacting in the back wall).

Figure 3 is a plot of I_0/Q vs d; it shows no systematic deviation from the inverse-square law down to a distance of 10 cm. It may therefore be concluded that, at the distances of interest here, no significant error is involved in measuring d to the geometrical center of the chamber.

Corrected ionization. In column 5 of the table are shown the ionizations corrected to correspond to a source strength of 1 mg and a distance of 1 cm. Their mean value is 135.8 ± 0.7 volts/min, where the uncertainty indicated takes into account the spread in the individual numbers and the estimated accuracy of the electrometer calibration. This value corresponds to ionization produced by secondary electrons from a polystyrene wall.

Had the wall been exactly "air-equivalent," the ionization would have been greater, since the stopping power per electron for electrons is less for air than for polystyrene. Laurence (*1*) has worked out the necessary correc-

TABLE 1—Observed Rates of Ionization

d (cm)	Q (mg)	I_0 (volts/min)	I_0/Q	$I_0 \times d^2/Q$
10.2	1.991	2.59	1.300	135.4
29.4	24.25	3.80	0.1569	135.6
30.15	50.1	7.60	0.1517	136.5
49.6	24.25	1.308	0.0538	133.0
51.0	50.1	2.66	0.0530	137.9
70.0	50.1	1.364	0.0272	133.4
99.8	97.7	1.360	0.01390	138.6
150.0	97.7	0.592	0.00606	136.4
			Mean	135.8

TABLE 2—Corrected Published Results

	Through 0.5-mm Pt (r/mg/hr at 1 cm)	
Reference	*Published value*	*Corrected for wall effect*
(*1*)	8.35	8.35
(*2*)	8.0	8.3
(*7*)	8.3	8.4
(*5*)	8.4	8.5
(*3*)	8.47	8.47
(*8*)	8.38	8.38
Present experiment	8.44	8.44
		Mean 8.41

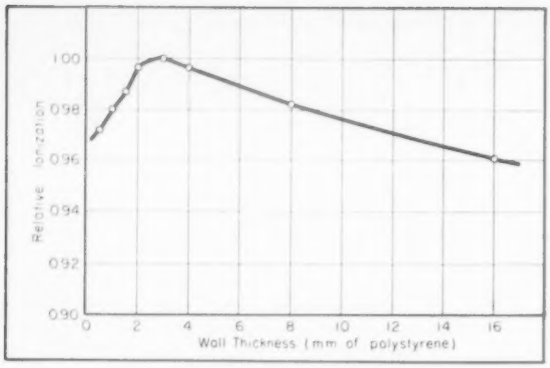

FIG. 2. Variation of ionization with wall thickness. (Source-to-chamber distance 50 cm)

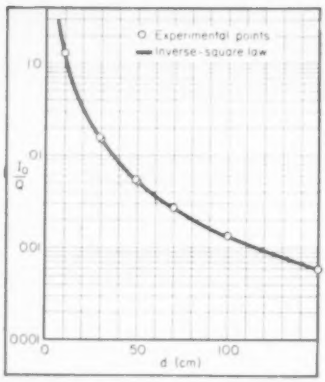

FIG. 3. Comparison of ionization rates with inverse-square law

tion factor in detail; in this case it amounts to 1.055.

Calculated output. It is now possible to calculate the roentgen output, at 1 cm, of 1 mg of radium filtered by 0.5 mm of platinum. It is equal to

$$J_0 C/V \times 60 \text{ min/hr} \times 3.00 \times 10^9 \text{ esu/coulomb} \times 1.055$$

where J_0 = rate of change of voltage on chamber, in volts/min, corrected to 1 mg at 1 cm; C = capacitance of chamber in farads; and V = volume of chamber in cm³. The result is 8.44 ± 0.07 r/mg/hr at 1 cm, or, converting to roentgens per hour at a meter (rhm), 0.844 ± 0.007 rhm/gm. Probable error is based on estimated errors in ionization, chamber volume and capacitance.

Discussion

In the first column of Table 2 are listed the results of several cavity-chamber measurements of the gamma-ray output of radium. They include the mean value obtained by Laurence (*1*), after correction to air-wall conditions, from results published prior to 1937, and a number of more recent values. Some of the differences between these values are due to the use of different wall corrections. In the last column of Table 2, Laurence's correction has been applied throughout, and the measurements of Kaye and Binks have been further corrected for absorption of the gamma rays in the wall. The corrected values yield a mean value of 8.41 ± 0.02 r/mg/hr at 1 cm.

It should be noted, however, that this value, obtained from measurements made with cavity chambers, differs appreciably from results obtained with free-air chambers. Thus Kaye and Binks (*2*), using an open-air chamber, found a value of 7.9 r/mg/hr at 1 cm, and Taylor and Singer (*6*), working at a pressure of 10 atmospheres, obtained 8.16 ± 0.04 r/mg/hr at 1 cm. The latter express some uneasiness about their correction for the absorption of radiation in the radium salt, and their value might be increased by about 1% on this account.

Anomalous graphite stopping power. One possible source of such a discrepancy has been pointed out by Dr. L. H. Gray, who has drawn our attention to the conclusion of Halpern and Hall (*9*) that the stopping power of graphite might be expected on theoretical grounds to be anomalously high. Halpern and Hall calculate the density effect—the reduction in the rate of energy loss of a charged particle in condensed matter due to the tendency of nearby atoms to screen more distant atoms from the effects of the electric field of the particle—to be negligible for most elements at energies below several Mev, but to be quite appreciable for carbon down to very low energies, the reduction amounting to about 10% at 1 Mev.

Dr. Gray points out that his own measurements of the ionization produced by the same flux of gamma radiation in graphite, paraffin wax, and gelatin ionization chambers (*10*) show no evidence of an anomalous effect in carbon as large as 10%. He adds that an effect of a few percent is not ruled out, and that should such an anomaly for carbon exist, the estimates of gamma-ray dose rate at 1 cm from 1 mg of radium based, as were his own, on ionization measurements in graphite ionization chambers, would be too high, and would be brought into closer agreement with the measurements in free-air chambers if some allowance were made for an anomalous stopping power of graphite.

It is worth noting, in this connection, that the calculations of Wick (*11*) lead to a density effect of a few percent in both carbon *and water* at energies of the order of 1 Mev. For the secondary electrons produced by radium gamma rays in carbon, the average effect would be around 3%. The corresponding corrected value of the radium output would be in the neighborhood of 8.2 r/mg/hr at 1 cm.

If, as the work of Wick indicates, the density effect is significant at these energies for all light materials, then any measurement of gamma-ray dose by means of a cavity chamber, and any estimate of the energy lost by ionization per gram of solid material (e.g., tissue) based on the measurement of ionization in a gas-filled cavity in the material, will be in error. It therefore appears that, until an accurate means of evaluating the density effect under these conditions becomes available, all such values must be suspected of being too high.

* * *

We are indebted to Mr. R. J. Smith of the Electricity Section for calibrating the electrometer and determining the capacitance of the ionization chamber.

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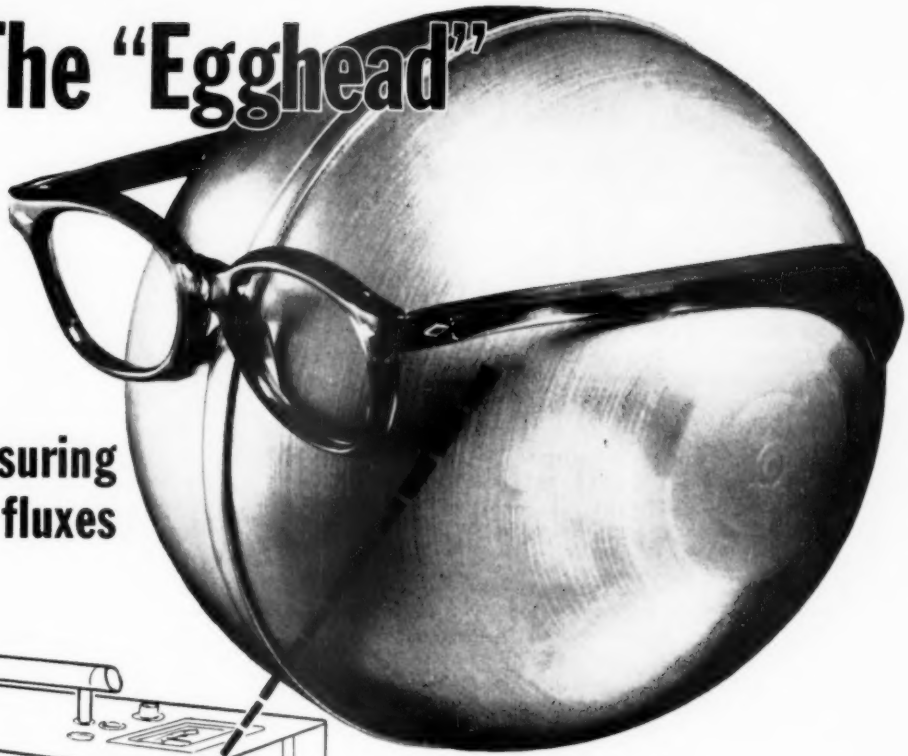

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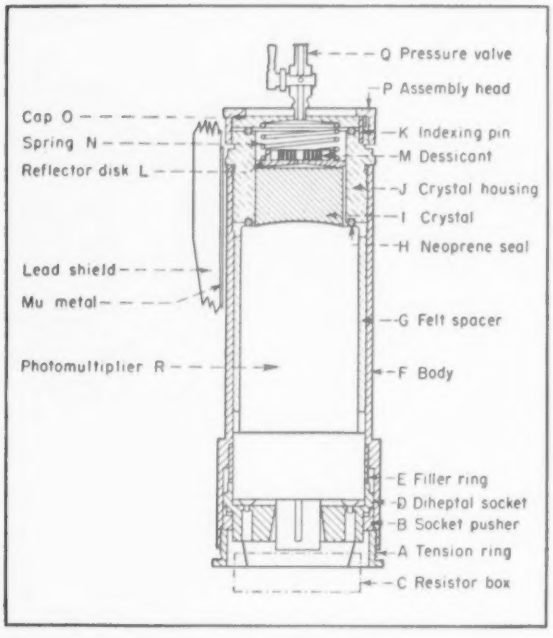

FIG. 1. Cross section of assembled housing

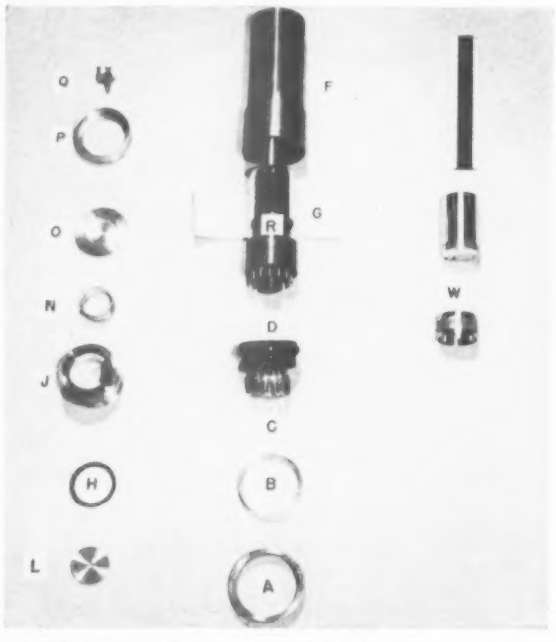

FIG. 2. Disassembled housing. Crystal, dessicant are not shown; W is lapping device

Rugged Scintillation-Counter Housing for Biological Applications

By L. E. PREUSS
Physics Department, Edsel B. Ford Institute for Medical Research Detroit, Michigan

The scintillation counter is particularly useful in biological and clinical tracer research because of its high gamma sensitivity. Such applications frequently necessitate rough handling of the instrument, while the scintillation counter itself is best adapted to bench work. This rugged use in biological applications demands a special and sturdy design.

Criteria

The first requirement for the housing is portability. The design should allow operation in any position. Second, the housing must be sturdy enough to serve as a base for heavy lead and magnetic shielding. Third, the design must allow good optical coupling between the crystal and the photomultiplier. Related to this, an efficient reflecting surround is necessary to direct back to the photocathode that light which has escaped from the crystal surfaces not in juxtaposition with the photocathode. Fourth, where the scintillation crystal is of a hygroscopic nature, a dessicated environment must be provided and a drying system must continuously maintain the surround at a very low concentration of available moisture over a long period. Finally, the unit must allow simple assembly under dry-box conditions with easy replacement of crystal and photomultiplier.

The device described is to be used only for the detection of gamma radiation, particularly that from I^{131}. This eliminates the necessity of thin windows for α or β work.

The components chosen for the design are a 5819 photomultiplier and a NaI (thallium activated) scintillation crystal. The 5819 is chosen because of its head-on design and large photocathode area with large pulse size and consequent ease of discrimination against dark-current pulses. The NaI crystal is used because of the large size and variety of single crystals available.* These crystals may be obtained up to 1½ in. in diameter, large enough to cover the sensitive area of the photocathode window. The emission spectrum of the NaI(Tl) is at 4,100 angstroms. This is on the ultraviolet end of the sensitivity curve for the 5819 and about 25% below the maximum sensitivity value of about 4,800 angstrom units.† The high affinity of this crystal for water necessitates dry-box operation with consequent problems.

* Harshaw Chemical Company, Cleveland, Ohio.

† Data sheet 5819-5-50 (R.C.A. Tube Department, Harrison, N. J.).

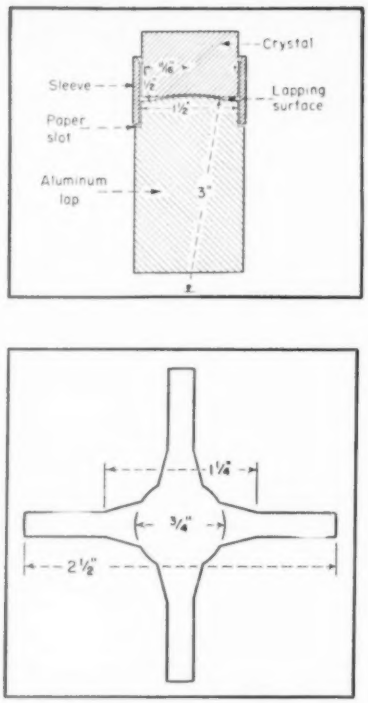

FIG. 3. (Top) Cross section of lapping device. (Below) Shape of abrasive cloth

A cross section of the housing assembly is shown in Fig. 1. The main body of the housing, *F*, is made of brass tubing with outside and inside diameters of 2½ and 2¼ in. respectively, within which the 5819 tube, *R*, is positioned. Since the 5819 production tolerances† may vary through ⅛ in. in diameter and ⅜ in. in height, the dimensions of *F* should be made to accommodate the largest obtainable tube. This allows routine replacement.

The tube is centered in *F* with a 3/16-in. thick soft felt spacer pad, *G*, that surrounds the glass envelope and protects it from impact against the body. The body *F* is built up at the base to 1¾-in. outside and 1 9/16-in. inside diameter to accommodate the tube base.

The NaI crystal, *I*, 1½ in. in diameter and 1 in. high, is lapped to fit snugly against the surface of the window of the photocathode. The inside walls of the aluminum crystal housing, *J*, are all highly polished to provide good reflection for the scintillation quanta. Sharp "V" threads, 32 per inch with 27/32 in. engagement, are used to fit *J* to *F*. The crystal is pushed snugly against the photocathode window by means of the reflector disk, *L*, and spring, *N*. The aluminum disk, *L*, is highly polished on the crystal side, and a center hole and cone-shaped "ceiling" are provided to free any air bubbles entrapped during assembly.

The dessicant, *M*, is a strip of press-extruded metallic sodium coiled into a loose disk about the size of a dime. It fits in the top of *L* and may be held in place by a clip. The aluminum cap, *O*, seals the unit by seating against a square ⅛-in. neoprene gasket. The cap also has a cone-shaped ceiling to free air bubbles. The pressure valve, *Q*, is an ordinary B.D.L.S-1, one-way syringe stopcock. This valve is convenient for filling the crystal chamber during the first assembly, but is best replaced by a plug for routine use. The aluminum assembly head, *P*, tightens the cap, *O*, against the upper neoprene ring seal by means of sharp "V" threads, 28 per inch with ½-in. engagement. The indexing pin, *K*, prevents rotation of *O* during assembly.

The 5819 photomultiplier is snugged against the neoprene ring, *H*, by means of the tension ring, *A*, which exerts a force upwards against the socket pusher, *B*, which in turn is seated against the diheptal socket *D*.‡ The filler ring, *E*, may be necessary as a tube-base centering sleeve to compensate for size variations due to production tolerances. This ring will be custom made for each tube base.

To reduce bulkiness of *F* the top half of the diheptal socket is turned down to 2 9/16 inch diameter. Only the top half of the socket is used. Connections to socket terminals may be carried out by cable or be made directly in an insulated resistor box, *C*, in which the dropping resistors are soldered directly to the socket terminals.

Figure 2 shows the housing disassembled.

Mu-metal and lead shields are used with the probe. The lead shield may be made just as effective, but less massive, by utilizing the tapered design indicated in Fig. 1. This taper will still produce an equivalent number of half-value layers for gamma radiation directed towards the crystal.

Dry-Box Assembly

The housing may be put together in a dry box in about 15 minutes. For assembly, the crystal housing is fitted to the body. Then the 5819 is snugged against *H*. The interior of *J* is partially filled with dessicated paraffin oil (dessication may be produced by storage with strip metallic sodium). The crystal is now immersed in the oil, and the unit made up of *O*, *N*, *L*, and *M* is seated firmly with pressure from *P* against the neoprene seal.

Valve *Q* is open during the seating procedure to avoid hydraulic pressure on the fragile window of the tube. The oil level is brought up to the top of *Q* by means of injection by an ordinary hypodermic syringe with a 3-in. needle. The needle, inserted through *Q* and the center hole in *L*, will remove any air bubbles trapped there.

The neoprene seals must be soft enough to avoid undue localized stress on the tube window. Neoprene (D6-20341)§ used here was tested on a Shore durometer "A" at rating 35–45. This rubber may soften upon long exposure to the oil, and all parts must be free of machining oils and other contaminants before assembly. These materials dissolved in the paraffin oil may increase its absorption of the scintillation photon. Considerable caution must be observed throughout the assembly to avoid unnecessary pressure on the photocathode window. The seals will hold with only a slight pressure from *A*.

Crystal Lapping

Where intimate contact between crystal and photocathode window is desired, a lapping device may be used, Figs. 2 and 3. The face of the aluminum lap is cut to the exact contour of the photocathode window. Then, with metallographic abrasive paper or polishing cloth cut to the shape suggested in Fig. 3, the base of the crystal is lapped to fit the tube.

This more intimate fit of these surfaces will improve the over-all light collection efficiency. It has been the experience here that final polishing done by hand with silk metallographic cloth, plus Linde A or Linde B levigated alumina,¶ produces an excellent finish.

* * *

The author wishes to acknowledge the valuable technical assistance in the machining of this housing of W. Burris, Instrument Shop, Henry Ford Hospital, Detroit, Mich.

‡ Amphenol diheptal socket #59417 medium.

§ Detroit Gasket & Mfg. Co., Detroit, Mich.

¶ Linde Air Products Co., New York, N. Y.

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The True Body Dosimeter Principle

By W. A. SHURCLIFF

Research Department, Polaroid Corporation Cambridge, Massachusetts.

A peculiar type of error in dosimeter readings arises when a man wearing a dosimeter happens to be facing away from a radiation source, so that his dosimeter is partially shielded by his body and therefore reads too low. Existing types of dosimeters are designed only to measure the dose received by the dosimeter itself and not the dose received by the wearer. Most standard health-physics texts ignore this and equate dosimeter reading and wearer's dose (*1–3*).

The purpose of this article is to show that it is possible to design a device that will indicate the wearer's instead of the instrument's dose. Before examining this "true body dosimeter," let us pause to estimate the size of error incurred using conventional dosimeters.

Size of Error

The error in dose reading depends on the spectral energy distribution of the gamma radiation, which in turn depends on the type of radiation source.

Co^{60} source (1.3 Mev). A ¼-curie source was placed on a 4-ft stepladder. A survey meter, used instead of a dosimeter to speed up the experimental procedure, was placed on another stepladder 12 ft away.

When the author (a 150-lb male) stood behind the meter, it read 20 scale divisions. When I stood so that the radiation passed perpendicularly through my chest, the meter read 10 divisions. When standing so that the radiation passed transversely through my chest, the reading dropped to about 7 divisions. And when the radiation passed through my body longitudinally, the reading was about 2 divisions.

In practice, rays would seldom pass through an individual's chest exactly perpendicularly. The average angle from the perpendicular would tend to be about 57 degrees. Thus, in general, we may expect that the dose received by a person exposed in fixed orientation to Co^{60} radiation will be either equal to or more than twice the dosimeter reading, depending on whether he faces the source or turns his back to it.

Air-burst atomic bomb. A rough estimate of attenuation of gamma radiation from this source by a human chest can be made from the fact that the radiation existing a mile from the explosion covers the spectral range from 0–4.5 Mev, with 3 Mev being most representative (*3*). One can calculate that the attenuation produced by a 7-in. layer of water perpendicular to a beam of 3-Mev radiation is about 30%. Assuming that a human chest corresponds to such a layer of water, and that the chest is not perpendicular to the radiation, the attenuation figure could be larger, perhaps 40%.

Once again, the dosimeter reading error can be far from negligible. The true dose can be 60 to 70% larger than the dosimeter reading. The error will presumably be less, however, if there is much back-scattered radiation.

Contamination from underwater burst. First, the radiation tends to be much softer, with a mean energy of about 0.7 Mev (*3*). Since the human chest is more opaque to this radiation than to Co^{60} radiation, we may estimate that the attenuation is about 65–75% for perpendicular radiation, or perhaps as high as 85% at typical obliquity.

Second, contamination would create an extended source so that radiation would strike an individual from all angles. Thus the preceding attenuation must be balanced against the fact that radiation from all forward directions will reach the dosimeter directly, and ½ of the dose will be indicated correctly. The other half must first pass through the body, and it will produce only about ⅕ of the response it deserves. The over-all result is a reading too low by about 40%; in other words, the wearer's dose exceeds the dosimeter's by 60 to 70% of the latter.

It is a striking fact that when recording radiation approaching from all directions, the dosimeter will necessarily read low. Error is not a possibility but a certainty, and amounts to more than 50% of the reading.

Are Errors Important?

Reasons why high accuracy is not needed for dosimeters, especially for civil defense, include the effect of dose rate, the varying sensitivity of humans to radiation, complications caused by other injuries, and the limitations of medical treatments available in times of disaster. Despite these arguments, it seems clear that accurate evaluation

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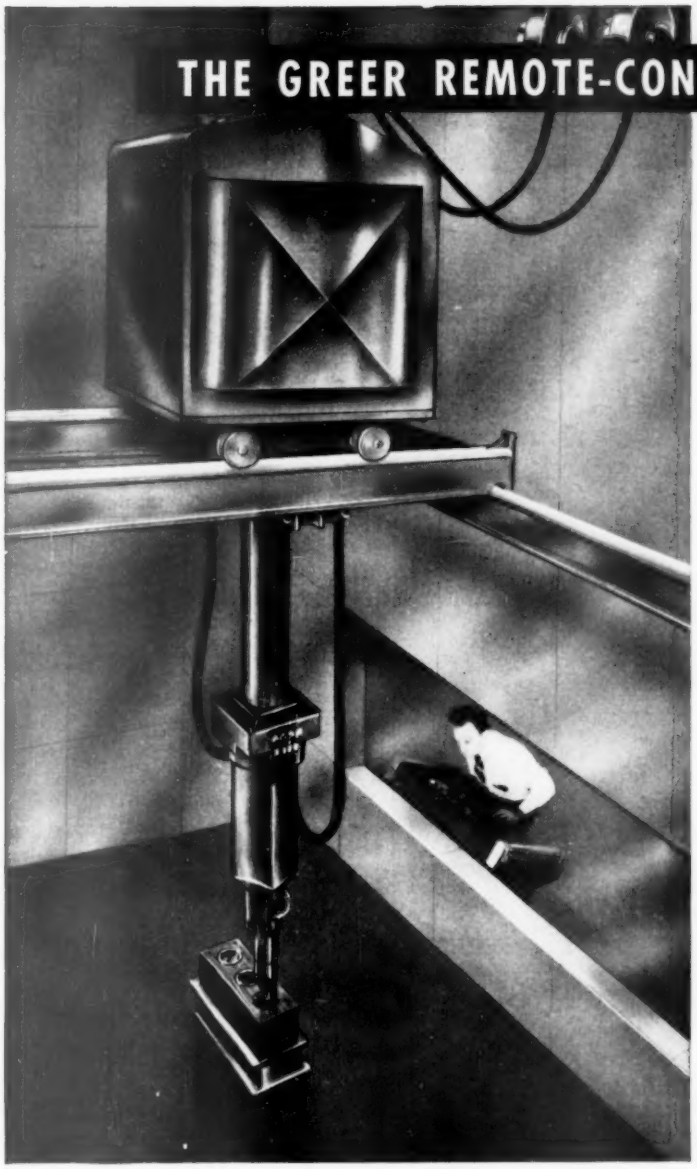

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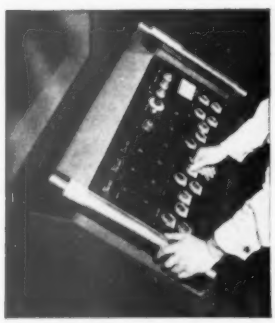
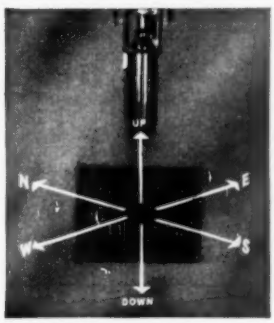
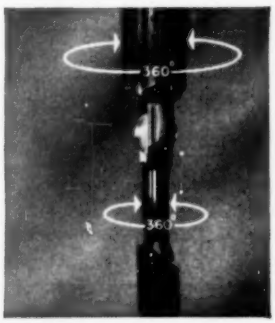


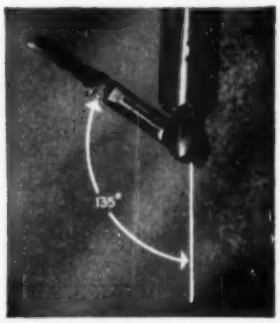
Push buttons control all motions. Rates of motion are determined by foot or hand control. Mobile control panel is mounted on "V" rail and keeps operator opposite work.



Positioning motions are (a) longitudinal, (b) transverse, and (c) vertical. These motions are provided by (a) mobile bridge, (b) trolley, and (c) hydraulic ram.



Rotation of both upper arm and wrist is accomplished through a system of gears and worm gear drive. System is adjusted to prevent interaction between motions.



Elbow action is provided by a 22" forearm rotating in a vertical plane through a 135° arc. This motion can produce 2100 inch-lbs. of torque with 100 lbs. load.

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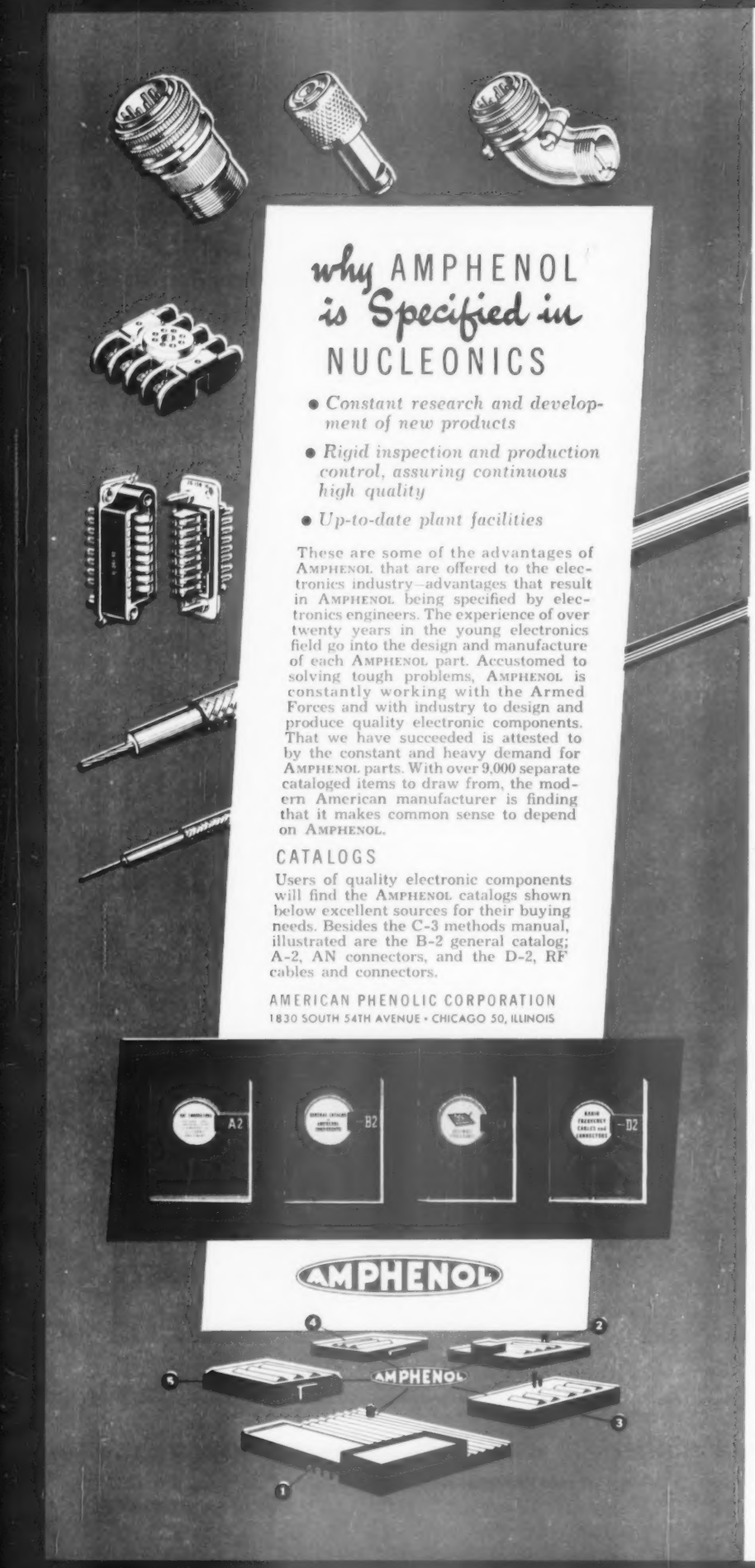
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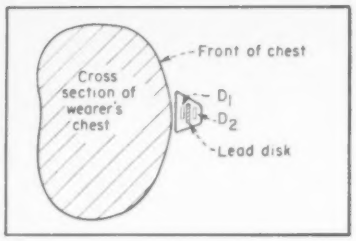

FIG. 1. Extrapolation type of true body dosimeter

of exposure is important. To relax accuracy requirements makes an already difficult situation even more so.

Published requirements on dosimeter performance stress the need for high accuracy (4). All common errors are required not to exceed 20%. The fact remains, however, that large errors must be expected frequently, even for dosimeters that would be rated perfect by the usual standards.

Half-way measures. Various half-way measures can help somewhat. Upward revision of dosimeter calibrations would tend to reduce the average error but would work rather poorly in the special situation where all radiation comes from the forward direction. Each person could wear two dosimeters, one in front and one in back. But this would work badly when radiation is incident from all directions since both dosimeters would read low.

True Body Dosimeters

The true body dosimeter principle consists of making such change in dosimeter design, and specifying such orientation of the dosimeter on the wearer's chest, that approximately the identical reading will result irrespective of whether the radiation approaches the wearer from ahead, from behind, or from both directions equally.

Two general methods have been worked out,* one called the extrapolation method and the other the compensation method.

Extrapolation method. In Fig. 1, D_1 and D_2 are two identical detectors. They may be two pieces of photographic film, two areas of a single strip of such film, two small disks of radiophotoluminescent glass, or two identical samples of any other type of small, accurate detector. Between the two detectors is an attenuator, e.g., a lead disk 10 mm thick and 15 mm in diameter, or a 5-mm-thick disk of the very dense alloy Hevimet.

The assembly is enclosed in a thin lead envelope serving the usual purpose

* Patent applications pending.

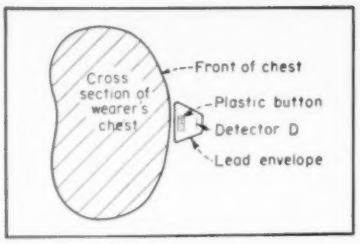

FIG. 2. Compensation type of true body dosimeter

of making the spectral response curve flatter. The lead envelope is in turn enclosed in a plastic case whose larger face carries a locking pin used in attaching the dosimeter so that D_1 is adjacent to the wearer's chest.

Such a device, together with an appropriate calibration chart, serves as a crude but effective true body dosimeter. Because of the shielding between the two detectors, their readings will differ for exposure from radiation incident from front or rear. The sign of the difference between readings indicates direction of the radiation; the ratio of the readings, magnitude of the correction factor. If the two detectors had the same reading, the inference would be that the radiation was incident from one side and that the readings were essentially correct.

The shortcoming of this device is that preparation of a calibration chart would require much empirical testing to evaluate the differences in detector readings in terms of true-body dose. Also, a slightly different calibration chart would be needed to take into account variations in human bodies.

Compensation method. In Fig. 2, let D be a small thin detector, positioned approximately as indicated within a special case. On the side of the detector toward the wearer's chest is a $\frac{1}{8}$-in.-thick button of Lucite or other material of low atomic number. Detector and button are enclosed in a lead envelope.

The device functions as follows. If the radiation comes from ahead of the wearer, a large portion of the response in the detector is produced directly by absorption of gamma radiation within the detector; some response is produced, of course, by secondary electrons knocked out of the lead envelope, but this effect is minor.

If the gamma radiation approaches the dosimeter from behind, i.e., via the wearer's body, there is again some absorption of the primary gamma radiation by the detector itself. But there is a much more important effect,

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namely the effect of electrons knocked forward (by the gamma photons) from the plastic button into the detector. It has been shown by Hine (5) that common plastics and other materials of very low average atomic number (low-Z materials) produce a great abundance of such forward-scattered electrons. There will also be many electrons knocked out of the lead layer in backward direction; Hine has shown that all high-Z elements produce relatively large quantities of backward-scattered electrons.

The important fact is that the scattered electrons may be far more important than the primary gamma radiation itself in producing response in the detector, provided the detector is very thin. If, for example, the detector consists of a photographic emulsion a few microns thick, the scattered electrons may be at least ten times more effective than the gamma radiation.

The success of the design resides in the asymmetry of the production of scattered electrons. Thus by flanking the detector on one side by low-Z material and on the other side by high-Z material, we provide an asymmetry, or modification factor M, tending to counteract the asymmetry of shielding by the wearer's body. (If the detector consists of a photographic emulsion supported by a low-Z base sheet, such as a sheet of cellulose acetate, this latter should face towards the high-Z button, so as not to lessen the asymmetry of the system.)

If it is arranged that M is 2, a 50% attenuation by the wearer's body will be fully compensated. The magnitude of M can be increased by decreasing the atomic number of the low-Z button and increasing its thickness. If desired, we could increase the thickness of the high-Z layer situated on the forward side of the dosimeter; this would increase the attenuation of radiation approaching the wearer from ahead, and so would further increase M.

Obviously the device is effective whether the radiation approaches the wearer from ahead, from behind, or both. In any of these situations there is only one reading—to be used directly as the wearer's true dose.

Although the devices have been tried out in principle (using photographic film as detector and also radiophotoluminescent glass), no adequate evaluations have been made. Adequate evaluation would require extensive testing, preferably using radiation from actual atomic bombs. Questions of energy dependence would arise, and although perfect solutions are certainly out of the question, it seems likely that reasonably good compromises would be found.

It is perhaps worth noting that almost any existing dosimeter of a type which employs lead shielding can be improved readily by partial application of the true body dosimeter principle; i.e., by attaching the device in fixed manner to the user's clothing, eliminating the lead shield on the side nearest the wearer, and doubling the thickness of the other shield. This creates a modification factor of perhaps 1.1 to 1.3 in typical situations, which cannot fail to reduce appreciably present errors due to intervention of the wearer's body.

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5. G. J. Hine, *Phys. Rev.* **82,** 755 (1951); also NUCLEONICS **10,** No. 1, 9 (1952)

Effect of Fall-Out from Atomic Blast on Background Counting Rate*

By A. FAFARMAN and M. H. SHAMOS

Department of Physics
New York University
New York, New York

In the course of some investigations of cosmic-ray gamma radiation, we have been making measurements of the background radiation for the past three or four months with a sodium-iodide scintillation detector on the roof of the main building, New York University, Washington Square, New York. The detector is shielded from terrestrial objects (other than the atmosphere) by 10 cm of lead and views a solid angle of approximately 2 steradians of the open sky. The sodium-iodide crystal (38-mm diameter by 25-mm height) is enclosed in a container which interposes 0.45 gm/cm² of Lucite and 0.65 gm/cm² of aluminum between the detector and its surroundings (about the range of 2.4-Mev electrons).

The detector has a counting rate of ~520 cpm (consisting almost entirely of gamma radiation) for energies >50 kev. Ordinarily, the maximum excursions in this counting rate are perhaps ±5%. There is a marked correlation with rainfall: the rate invariably rises due to the well-known phenomenon of deposition of atmospheric radioactive material in the rain water and on the apparatus.

It was anticipated that the atomic explosion at Yucca Flats, Nevada, on March 17, 1953 might result in an increase in the background rate. An exceedingly heavy rainfall commencing at ~1900, March 18, sent the rate up sharply. At 1030, March 19, the rate was 3,850 cpm, an increase of 600%. Most of this was due to rain water, as was demonstrated by removing a plastic cover from the apparatus, whereupon the counting rate dropped to 1,470 cpm. The remaining increased activity was presumably atmospheric. A thin-walled, 30 mg/cm², counter inside the laboratory recorded an increase in counting rate of 75%.

Counting rates 25 times greater than the usual cosmic-ray background were observed with a Victoreen Thyac model 389 radiation detector when the counter was placed adjacent to small pools of the rain water.

The radiation level on March 20 was decaying at the rate of about 1.5%/hr, consistent with the average value for the decay of fission-product radioactivity for this period.†

The fission products have altered the energy distribution of the background radiation considerably. Figure 1 shows differential energy distributions of the background radiation before and after the onset of the increased rate for energies below 100 kev. (The decrease in counting rates for energies immediately above the noise is due principally to the very high absorption by the photoelectric effect for these low-energy radiations.) The energy at which the broad maximum occurs is

* Research assisted by the U. S. Atomic Energy Commission.

† "Effects of Atomic Weapons," p. 251–3 (McGraw-Hill Book Co., Inc., New York, 1950).

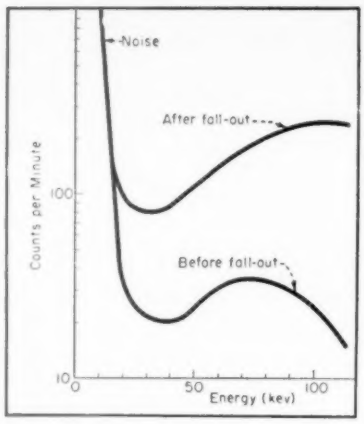

FIG. 1. Effect of fall-out below 100 kev †

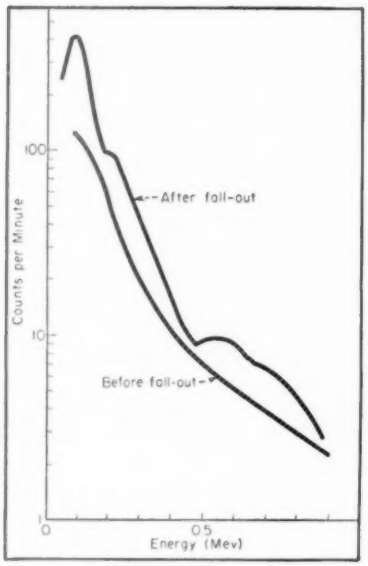

FIG. 2. Effect of fall-out below 1 Mev

related to the energy distribution of the incident radiation and the photoelectric absorption.‡

Figure 2 illustrates the differential spectra for energies below 1 Mev (none of the spectra in Figs. 1 or 2 have been corrected for the gamma energy dependence of the efficiency of the sodium-iodide detector or for absorption in the crystal container). It is seen that there appears to be a peak at 197 kev attributable to backscattering of gamma radiation from the lead shielding. Additional broad irregularities appear near 500 kev (annihilation radiation) and near 700 kev.

‡ This maximum may result from backscattering (Compton scattering) by the atmosphere of gamma radiation emitted from terrestrial sources (due to the energy dependence of the photoelectric vs Compton effects).

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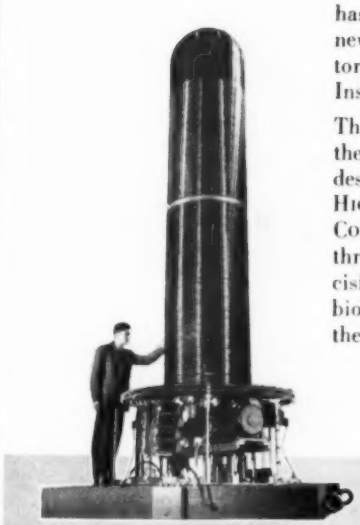

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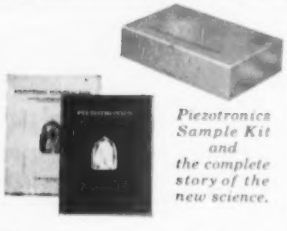

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LETTERS

Atomic Industrial Forum

[*In the May issue of* NUCLEONICS *(p. 70), the formation of the Atomic Industrial Forum, Inc., was reported. In the same issue, it was pointed out in an editorial (p. 9) that AEC clearance seemed to be an undesirable criterion for membership. The action reported below removes this objection.*—Editor]

DEAR SIR:

. . . With respect to the by-laws and the classes of membership problem, as you know the original purpose of dividing the membership into classes was to insure that the controlling group in the Forum would be made up of responsible individuals who, because of active participation in atomic matters, would be knowledgable in atomic affairs. After considerable discussion, it seemed to the Board of Directors that this objective could be better achieved if access to restricted data were not made the criterion for classification.

In the by-laws, as adopted this week, accordingly, provision is made for three classes of members: Members, Associate Members and Organization Members. Only individuals who are citizens of the United States are eligible to be Members or Associate Members. Moreover, in order to become a Member, an individual must, in the judgment of the Committee on Membership or the Board of Directors, have been, or currently be, engaged *to a substantial degree* in activities related to atomic energy. Associate Members, on the other hand, need not have been engaged to a substantial degree in such activities and may, indeed, be persons who only expect to be engaged in them in the foreseeable future.

The third category of members, Organization Members, is to be made up of corporations, associations, partnerships and trusts which have been, or are currently, or may reasonably expect to be, engaged in such activities.

We believe that the classification of members as now provided for in the by-laws is a sound and workable one and will assure that the active conduct of the affairs of the Forum is in the hands of experienced, responsible individuals who will have a sympathetic understanding of atomic problems.

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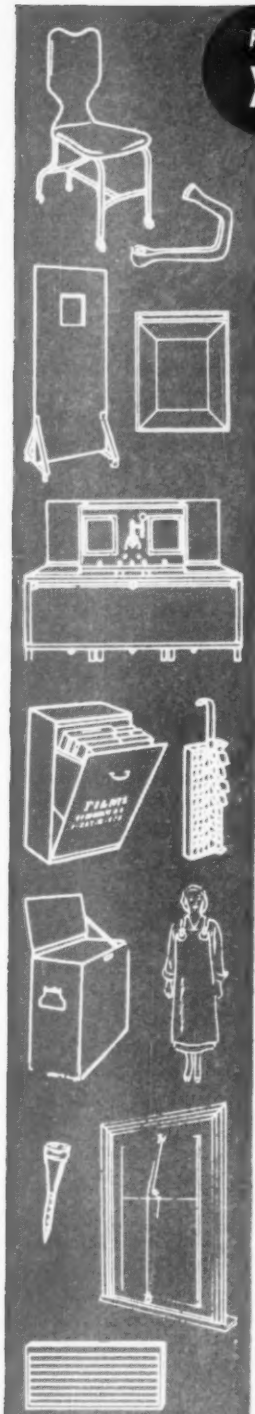

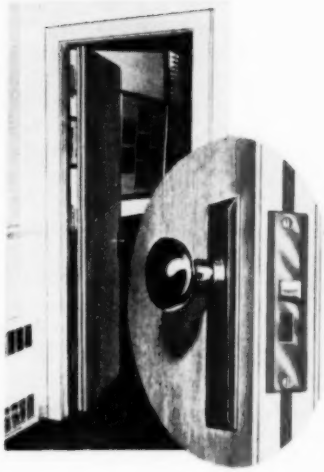

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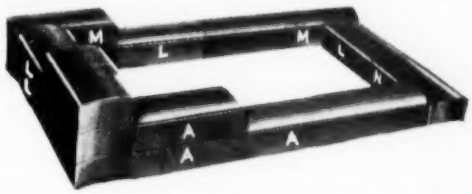

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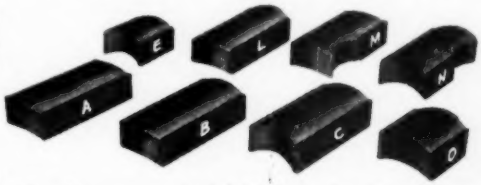

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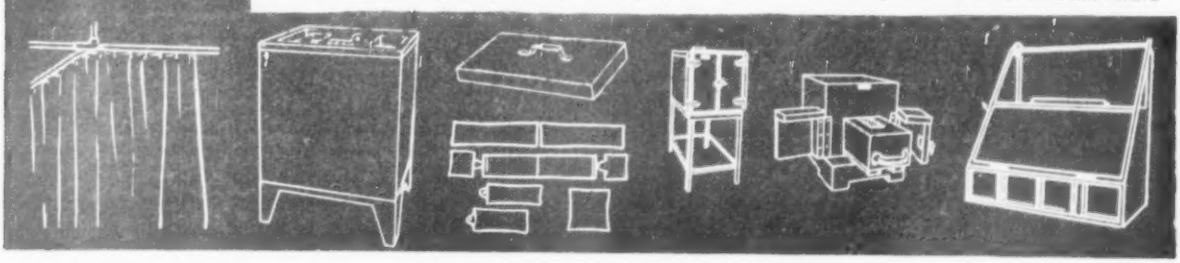

BOOKS

Annual Review of Nuclear Science—Vol. 2, 1953

Edited by J. G. BECKERLEY (Annual Reviews, Inc., Stanford, Calif., 1953, ix + 429 pages, $6). Reviewed by R. L. THORNTON, Radiation Laboratory, University of California, Berkeley, Calif.

The content of this volume can best be summarized by listing the chapter headings and the authors: *The Origin and Abundance Distribution of the Elements*, R. A. Alpher and R. C. Herman; *Energy Production in Stars*, E. E. Salpeter; *The Production and Distribution of Natural Radiocarbon*, E. C. Anderson; *Recent Progress in Accelerators*, E. L. Chu and L. I. Schiff; *Nuclear Reactions Induced by High Energy Particles*, D. H. Templeton; *Recent Studies of Photonuclear Reactions*, K. Strauch; and *Angular Correlation of Nuclear Radiation*, H. Frauenfelder.

Also *Subnuclear Particles*, J. S. Blair and G. F. Chew; *Radiation Effects in Solids*, G. J. Dienes; *Isotopes*, J. Bigeleisen; *Nuclear Moments*, B. T. Feld; *The Experimental Clarification of the Theory of β-Decay*, E. J. Konopinski and L. M. Langer; *β-Decay Energetics*, C. D. Coryell; *Origin and Propagation of Cosmic Rays*, L. Biermann; *Advances in Nucleon-Nucleon Scattering Experiments and Their Theoretical Consequences*, G. Breit and R. L. Gluckstern; and *High Energy Fission*, R. W. Spence and G. P. Ford.

When this listing is considered together with that for the preceding volume and that projected for volume 3, it is clear that the editors are making an effort to cover the field in a reasonably comprehensive manner. However, a consequence of this, perhaps inevitable in view of space limitations, is a tendency toward superficiality and a lack of critical discussion and evaluation.

As is to be expected, there is considerable variation in the quality of the individual articles. Those dealing with the angular correlation of radiations, with the subnuclear particles, and with nucleon-nucleon scattering seemed particularly good to this reviewer. On the other hand, there seemed to have been little of importance in accelerator progress, and the survey of nuclear reactions produced by high-energy particles appeared somewhat inadequate, especially in the discussion and evaluation of the theoretical attempts to describe the observed phenomena and in the discussion of the cosmic-ray data. In general, the topics selected were treated adequately and by writers whose competence in the several fields is undoubted.

In some instances, it would seem that more editorial work would improve the presentation. As is to be expected, several authors have occasion to discuss the same topic. It would seem that a considerably more detailed discussion would result if one author dealt with this subject and appropriate references were made to this discussion when desirable. Instances of this failure to correlate properly the various papers are the discussion of the shell model of the nucleus and Hamilton's theory of the angular correlation of radiations.

The bibliographies are quite complete and the index seems very adequate. The printing, etc., is quite satisfactory, and the price is very reasonable for technical books nowadays.

In general, this book can be recommended as a useful and convenient summary, but one in which there is considerable room for improvement which it may be hoped will be exploited in future volumes.

Nuclear Stability Rules

By N. FEATHER (Cambridge Monographs on Physics, Cambridge University Press, New York, 1952, ix + 162 pages, $4). Reviewed by CHARLES D. CORYELL, Department of Chemistry and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Mass.

The author of this monograph, Professor Feather, has long been a leading experimentalist in radioactivity and has contributed greatly to the systematization of experimental data on nuclear decay processes. This four-chapter monograph represents a survey of information concerning the stability properties of the ground states of nuclides in which much of the data is marshalled graphically.

The chapters are *Systematics of Stable Nuclei*, *Regularities in α-Disintegration*, *Regularities in β-Disintegration*, and *Spontaneous Fission and the Number of the Elements*, with the two middle ones occupying three-fourths of the book and the last only four pages.

The treatment uses recent theoretical developments very sparingly, referring for instance to no theoretical treatment of nuclear shells. The first chapter gives systematizations of purely empirical nature. The treatment of α-disintegration rates is cumbersome and not very enlightening. The treatments of β^-, β^+, and electron-capture disintegration rates are based on involved empirical induction giving results that are surpassed in several recent reviews. The treatment of ground-state β-transition energies is satisfactory, but interpreted with unduly complicated descriptive equations.

The literature coverage on experimental papers is rather complete, numbering about 320 entries covering publications to the end of 1951. With each reference is a listing of the places in the text where the paper is discussed.

The book is a very honest one with rather limited horizons. It serves to point up many areas in which more information is needed, and it aims "so to marshal the experimental facts that the theorist is inspired. . . ." It seems to lack in some places the elements of inspiration, at least for the student of nuclear science who wants to win a balanced view, from the standpoint of both experiment and theory, of the principles of nuclear stability.

BOOKS RECEIVED

Signal, Noise and Resolution in Nuclear Counter Amplifiers, by A. B. Gillespie, McGraw-Hill Book Co., Inc., New York (or Pergamon Press Ltd., London), 1953, xii + 155 pages, $4.50. First book in a series on applied modern physics and communications. (*To be reviewed.*)

Advances in Biological and Medical Physics, vol. 3, edited by John H. Lawrence and C. A. Tobias, Academic Press Inc., New York, 1953, x + 368 pages, $8. (*To be reviewed.*)

Experimental Nuclear Physics, vol. 1, edited by E. Segrè, John Wiley & Sons, Inc., New York, 1953, ix + 789 pages, $15. This first volume of a projected series contains sections by H. H. Staub, H. A. Bethe and J. Ashkin, N. F. Ramsey, and K. T. Bainbridge. (*To be reviewed.*)

The Theory of Homogeneous Turbulence, by G. K. Batchelor, Cambridge University Press, New York, 1953, xi + 197 pages, $5; one of the Cambridge monographs on mechanics and applied mathematics.

The Comets and Their Origin, by R. A. Lyttleton, Cambridge University Press, New York, 1953. x + 173 pages and 34 photographs of the most celebrated comets, $5. After setting down the known facts about comets, this book goes on to account for their origin and to explain how comet tails are formed.

Wave Propagation in Periodic Structures, (2nd edition with corrections and additions) by Leon Brillouin, Dover Publications, Inc., New York, 1953, xii + 255 pages, $1.75 (paper), $3.50 (cloth).

Radiations and Living Cells, by F. G. Spear, John Wiley & Sons, Inc., New York, 1953, xii + 222 pages, $3.50. (*To be reviewed.*)

High Energy Nuclear Physics, proceedings of the third annual Rochester conference, Dec. 18–20, 1952, compiled and edited by H. P. Noyes, M. Camac, and W. D. Walker, Interscience Publishers Inc., New York, 1953, 110 pages, $2. This is the complete record of the conference, a summary of which was published in NUCLEONICS, Feb. '53, p. 42.

ALSO OF NOTE

Isotopes—Radioactive and Stable. This is the latest catalog and price list of isotopes and associated services which are available from Oak Ridge National Laboratory, effective Jan. 1, 1953. Each isotope is listed on a separate page with such information as half-life, radiations, production reaction, target, yield, irradiation time, cross section, specific activity, and other activities present. Handbook-type information is given on other materials and services available. The catalog is loose-leaf bound, and supplementary pages and price lists will be issued to customers from time to time. *Isotope Sales Department, Oak Ridge National Laboratory, Oak Ridge, Tenn., $1.*

Mass Spectroscopy in Physics Research, National Bureau of Standards Circular 522, Government Printing Office, Washington, 1953, vi + 273 pages, $1.75.

This is the proceedings of a conference held Sept. 6–8, 1951, at the National Bureau of Standards. It contains the texts of 36 papers given and records of the discussions. The circular, in effect, summarizes a decade of work in mass spectroscopy and its use in physics research.

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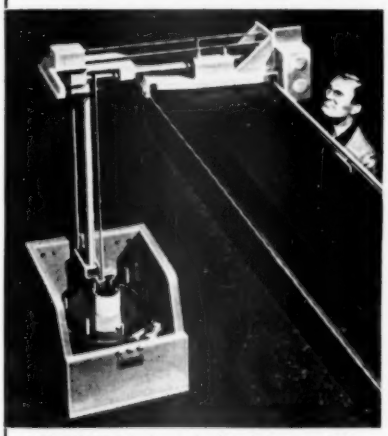

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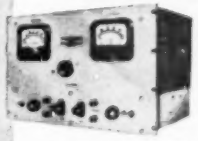

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EA-48	160 to 1500 Volts	0-125 MA	Less than 20 MV	0.5%

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NEWS

AEC Budget for Fiscal 1954 Cut by $480-million; Will Not Support Pilot Plants for Reactor Power Stations

The original budget for the Atomic Energy Commission for fiscal 1954, prepared by the Truman administration, has been slashed by about $480 million by President Eisenhower's budget makers. Details of the cut have not been made available, but it is understood that all new starts on nonmilitary reactors, including proposed pilot plants for generation of power, have been eliminated from the budget.

The original AEC budget called for a total of about $1.6-billion in new appropriations. These new funds, plus carryover funds and reappropriation of money previously advanced by Congress, would have permitted total expenditures of $2.7-billion. The new budget cuts new appropriations to about $1.2-billion and spending to about $2.3-billion.

AEC had been expected to ask for funds this year to start construction of one or more small nonmilitary reactors of types believed suitable for electric power production. Industry groups interested in nuclear power had hoped that one or more of these test plants would help establish the feasibility of power reactor designs. If such plants are to be started at all this year, they probably will have to be financed with private funds.

According to Rep. W. Sterling Cole (R., N. Y.), chairman of the Joint Congressional Committee on Atomic Energy, the budget cut will not require a halt in the construction of the Portsmouth, Ohio, uranium extraction plant or any other expansion of AEC production facilities. Cuts in the expansion program will be minor, most of the trimming will be on less essential expenditures.

Also eliminated were funds for actual construction of propulsion reactors for aircraft and for an aircraft carrier. These reactors, however, were not yet ready for final construction. Research contracts have already been let for both these projects, and they will be continued.

Contracts for nuclear powered submarines were not affected by the budget cuts. Also untouched were scheduled funds—the amount is secret and will remain so—for development of nuclear weapons.

Dual-Purpose Reactor Being Built in Great Britain

Work has started in England on the construction of a reactor to produce both plutonium and power in Cumberland, across the river from Sellafield where the British plutonium production reactors are situated.

It is not expected that the new breeder will produce power that is cheap by comparison with conventional facilities. The British view the reactor as an opportunity to increase the total power available in the country as well as the plutonium production capacity, and hope to have it in operation in about three years.

It is said that the reactor will be an orthodox uranium reactor with a pressurized core through which a heat-exchange medium will flow. The nature of the heat-exchange medium has not yet been determined. There are no natural supplies of helium in Great Britain, and experiments are being done with heavier gases and liquid metals.

No statement has been made on the capacity of the new reactor, but it is believed that the plant will generate about 50,000 kw of electricity.

There are as yet no breeder reactors in England. A small experimental model is nearing completion at Harwell, and a large pilot model is still in the design stage.

12 More Companies Join Power-Reactor Study Group

Twelve more companies have joined the feasibility study program for power reactors being conducted by the Dow Chemical Co. and the Detroit Edison Co. under an agreement with the Atomic Energy Commission.

These additions bring the total number of companies associated with the Dow-Detroit project to 25 (NU, Nov. '52, p. 108). This composite of industrial concerns and utility companies will carry on the research and development program approved by AEC in April, 1952.

The investigations proposed by Dow-Detroit are in keeping with AEC's own power reactor program and will intensify the improvement of reactors along the lines selected. Much of the work by the two companies, estimated at about $1-million in direct costs for the 1953 calendar year, will be carried out in their own laboratories.

The associated companies will provide security-cleared personnel qualified to help on the Dow-Detroit work. Each company will assign one or more men on an essentially full-time basis, and these men will function as regular employees of either Dow or Detroit Edison. To add management experience to the project, a limited number of executives will get security clearance.

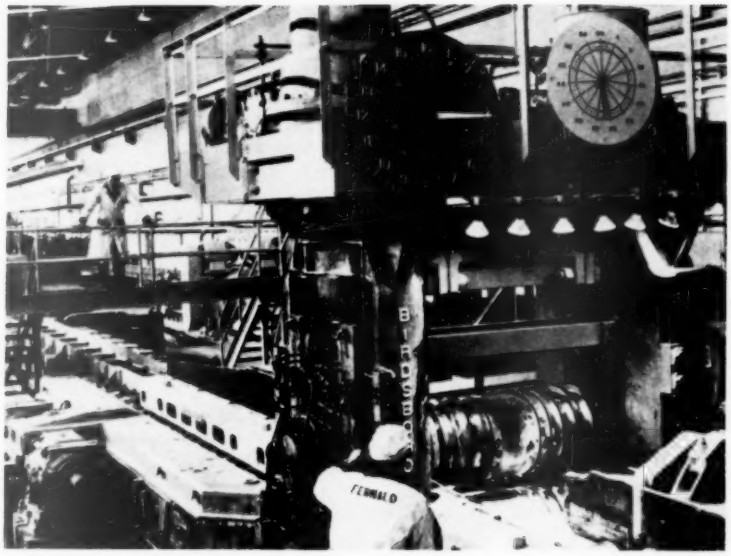
The new companies associated with the project are Consolidated Gas Electric Light and Power Co. of Baltimore, Hartford Electric Light Co., Niagara Mohawk Power Corp., Potomac Electric Power Co., Rochester Gas & Electric Corp., Southern Co., Allis-Chalmers Mfg. Co., Bendix Aviation Corp., Ford Motor Co., United Engineers & Constructors Inc., Atlantic City Electric Co., and Gibbs & Cox, Inc.

Thermonuclear Reactions Studied at Livermore Lab

Work on thermonuclear reactions has been underway at the Atomic Energy Commission's laboratory at Livermore, California, for some time. This work, which is under the direction of Edward Teller, led to the detonation of a thermonuclear device at Eniwetok last November.

AEC has never released information on the purpose of the Livermore laboratory, but these facts were made known in an article in *Fortune*. When questioned about the information given in the article, AEC officials in both Washington and San Francisco refused to confirm or deny the story.

The Livermore laboratory is operated by the California Research and Development Corp. under contract with AEC.



PRIMARY MILL, followed by continuous finishing mill, rolls uranium into bars for further fabrication into reactor slugs

Breeding Successful

The first experimental verification of the breeding principle was announced on June 4 by Gordon Dean, chairman of the Atomic Energy Commission. The work was done with the Argonne National Laboratory's Experimental Breeder Reactor at the National Reactor Testing Station, Arco, Idaho.

In making the announcement, Dean said, "The reactor is operating in such a way that it is burning up U^{235} and, in the process, it is changing non-fissionable uranium into fissionable plutonium at a rate that is at least equal to the rate at which the U^{235} is being consumed."

Further details will be published in the July NUCLEONICS.

Ohio Feed Materials Plant Nearing Completion

The Feed Materials Production Center, under construction at Fernald, Ohio, for the Atomic Energy Commission is nearing completion, and some portions of the plant are already in operation. The manufacture of uranium feed materials is an integral part of the process chain leading to the production of fissionable materials.

FMPC is a completely integrated series of plants whose function is to convert raw uranium ore into highly pure uranium metal in various shapes. The process is so designed as to reclaim essentially all of the uranium contained in the ores, and also a substantial portion of the chemicals used in the various process steps.

Among the intermediate products produced in the process are "orange oxide" (UO_3), "green salt" (UF_4), and metal ingots, rods, and slugs. The picture above shows the interior of one of the buildings of the plant which houses a primary Birdsboro mill which is followed by a continuous finishing mill used to roll uranium into bars for further fabrication into slugs for reactors.

Plans for FMPC, which is under the supervision of AEC's New York Operations Office, were first announced early in 1951. Catalytic Construction Co., Philadelphia, has the architect-engineer contract; George A. Fuller Co., New York City, has the construction contract; and National Lead Co., Ohio, has the operating contract.

Of the total $78-million estimated cost of FMPC, Catalytic will expend about $30.4-million for architectural and engineering work and for process equipment procurement. About $47-million will be spent by Fuller for construction work. Acquisition of the 1,050-acre site cost $600,000.

Albert L. Baker Dies; Directed Vitro Corp.

Albert L. Baker, chairman of the board of Vitro Corporation, and credited with a major role in the engineer designing and building of the Oak Ridge gaseous diffusion plants, died last month at the age of 55. Mr. Baker was one of the original board members of the newly formed Atomic Industrial Forum, Inc.

North American Aviation Ready to Build Pilot Plant for Reactor Power Station; Looking for Customers

North American Aviation, Inc., has announced that it has designed and is ready to build a pilot plant for a nuclear powered electric generating station. The design was done under contract with the Atomic Energy Commission, and the company is now seeking private industrial firms, or a government-industry combination, that will be interested in having such a pilot plant built.

Estimated cost of the plant is $10-million. The company stands ready to begin construction engineering immediately, and expects that it could have the plant in full operation in 2 years.

According to Chauncey Starr, director of the company's atomic energy research department, the pilot plant could generate electricity that would cost about $1\frac{1}{2}$ times the cost of electric power from conventional plants. Starr told NUCLEONICS that the promise of lowering these costs by gaining experience with pilot plants is so great that he expects that in 25 years the only plants built will be powered by nuclear reactors.

The pilot plant, which would generate 8,000 kw of electrical power, would be powered by a graphite-moderated, liquid-metal-cooled, thermal reactor. The reactor would be designed for power only, but could be converted to dual purpose use at any time.

The fuel for the reactor would be natural uranium, slightly enriched uranium, or U^{233}. In the case of the U^{233} fuel, the reactor would be loaded

with thorium and a starter charge of U^{235}. The U^{233} fuel would be produced by the capture of neutrons by the thorium. It might be necessary to add booster charges of U^{235} at intervals during the operation of the reactor.

Bill Introduced to Amend McMahon Act

Major revision of the Atomic Energy Act of 1946 to promote industrial development of nuclear power has been proposed in a bill (HR-4687) introduced in Congress by Rep. James E. Van Zandt (R., Penna.), a member of the Joint Congressional Committee on Atomic Energy.

The bill, said to represent the views of others on the Joint Committee, goes along with proposals of the Atomic Energy Commission to permit private ownership of fissionable materials and reactors, a government guarantee of supplies of fissionable materials for owners of private power reactors, and relaxation of present restrictions on outright patents for industry. In addition, Van Zandt wants to make some revisions that do not show up in AEC's recommendations.

Most significant probably is his demand that AEC be forbidden from selling electric power except where it is a byproduct of production of fissionable materials. Thus, AEC—legally, at least—could harness the heat produced in the Hanford and Savannah River plants to produce electricity in conjunction with plutonium. But the Commission would be hard-pressed to find ways of building a large-scale reactor primarily to produce power.

This would not bar Government construction of additional experimental reactors like the Experimental Breeder in Idaho or the Homogeneous Reactor at Oak Ridge, if AEC absorbed any power output for its own operations.

Another significant proposal by Van Zandt is that AEC be permitted to assist friendly foreign governments by exchanging additional information on nuclear power. This would mean large-scale revision of present security restrictions on interchange of data with foreign countries.

Van Zandt has considerable support among other members of the Joint Committee for his proposed restriction on Government sales of nuclear power. He faces tougher sledding, however, with any attempt to broaden the present interchange of information with other countries.

He isn't expected, however, to fight for every point in his bill. Apparently his principal objective was to give the Joint Committee concrete recommendations out of which it could begin hammering out an amendment of the McMahon Act as quickly as possible.

Here's what Van Zandt told NUCLEONICS about his proposals:

"This is what might be called a minimum bill, designed first to allow private enterprise to own, or hold on long-term lease, the material to run atomic power plants; second, to authorize the AEC to regulate those plants; third, to prevent an atomic TVA by prohibiting the AEC from selling power except as produced in conjunction with manufacture of weapons materials; fourth, to allow patents on privately finance nonweapon developments; and fifth, to allow the United States to give assistance to friendly foreign governments in building atomic power plants whenever it is in the interest of national security to do so.

"My main purpose in introducing this bill was to place before the Congress and the Joint Committee on Atomic Energy the principal elements of the problem of development of atomic power."

Atomic Energy Commission Announces Power Policy and Details of Revised Atomic Energy Act

Because it feels that "there is considerable optimism that economic nuclear power can be obtained within a few years," the Atomic Energy Commission has decided that "now is the time to announce a positive policy designed to recognize the development of economic power as a national objective." On May 26, the AEC revealed the details of its long awaited policy statement and a proposed new atomic energy act. In so doing, AEC cautioned that: "As a nation, we should not delay the development of this great potential source of energy for constructive purposes until circumstances force us to attempt its practical realization on a short time scale."

At the same time that the AEC recommendations were made public, Rep. W. Sterling Cole (R., N. Y.), chairman of the Joint Committee on Atomic Energy, stated that public hearings on atomic energy legislation were set to start on about June 15 and to run for two weeks.

Below are the AEC policy statement and AEC's proposed new law:

1. We believe the attainment of economically competitive nuclear power to be a goal of national importance. Reactor technology has progressed to the point where realization of this goal seems achievable in the foreseeable future if the nation continues to support a strong development effort. It would be a major setback to the position of this country in the world to allow its present leadership in nuclear power development to pass out of its hands.

2. Accordingly, we recognize it as a responsibility of the Commission to continue research and development in this field and to promote the construction of experimental reactors which appear to contribute substantially to the power reactor art and constitute useful contributions to the design of economic units.

3. In addition, it is the conviction of the Commission that progress toward economic nuclear power can be further advanced through participation in the development program by qualified and interested groups outside the Commission.

4. We recognize the need for reasonable incentives to encourage wider participation in power reactor development, and propose the following moves to attain this end:

(a) Interim legislation to permit ownership and operation of nuclear power facilities by groups other than the Commission.

(b) Interim legislation to permit lease or sale of fissionable material under safeguards adequate to assure national security.

(c) Interim legislation which would permit owners of reactors to use and transfer fissionable and by-product materials not purchased by the Commission, subject to regulation by the Commission in the interest of security and public safety.

(d) The performance of such research and development work in Commission laboratories, relevant to specific power projects, as the Commission deems warranted in the national interest.

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are presently granted to outside groups as may seem appropriate to the Commission and consistent with existing law.

(f) Consideration of a progressively adjusted code for safety and exclusion area requirements as may appear reasonable in the light of operational experience with reactors. Competent state authorities will be encouraged to assume increasing responsibility for safety aspects of reactor operation. Financial responsibility associated with reactor operation will be assigned to the owners, in keeping with normal industrial practice.

(g) Giving full recognition to the importance of reactor technology to our national security, a progressively liberalized information policy in the power reactor field as increasing activity justifies.

5. It is the objective of this policy to further the development of nuclear plants which are economically independent of government commitments to purchase weapons-grade plutonium.

6. We view the next few years as a period of development looking toward the realization of practical nuclear power. On this basis, we conclude that the time is not yet at hand for the report called for in Section 7(b) of the Atomic Energy Act of 1946.

Form of Proposed Legislation

The proposed legislation is in the form of a separate act rather than a series of individual amendments to sections of the Atomic Energy Act. The decision to recommend a separate act is based primarily on the advantages of a legislation proposal which is in itself reasonably self-explanatory and which is concerned primarily with the subject of atomic power.

It should be noted, however, that under Section 12 of the proposed legislation the provisions of the Atomic Energy Act would remain in effect except as modified by the new legislation. Among the important provisions of the Atomic Energy Act which would remain in effect would be (a) the espionage provisions of Section 10 in respect to unauthorized disclosures of restricted data, (b) the limitations of Section 10 upon the exchange of information with foreign countries, (c) the prohibition on private manufacture of atomic weapons, (d) the authority of the Commission to assist independent research and development work by other persons, (e) the licensing requirements of Section 5(b) relating to transfers of source material, (f) the Commission's authority under Section 5(a)(5) to requisition facilities capable of producing fissionable material, and (g) the licensing requirements of Section 4(e) with respect to the transfer of important component parts of any facility capable of producing fissionable material.

Interim Nature of Legislation

The proposed legislation is designed to effect only such changes in the Atomic Energy Act, and to provide only such supplemental authority to the Commission, as are considered necessary or desirable at the present time. At a later time it will presumably be desirable to consider other possible changes in the Atomic Energy Act relating to (a) the Commission's role vis-a-vis other Federal and State agencies in respect to the safety aspects of power reactors and their by-products, (b) the extent to which the Government should control private mining, processing and sale of uranium ore for use in power reactors, (c) the necessity for licensing control over the domestic sale of important component parts of power reactors, and (d) the procedural aspects of the issuance or refusal of licenses to applicants interested in the construction and operation of power reactors. Additional legislative questions will no doubt become apparent in the course of the development of atomic power.

Outline of Legislation

The provisions of the proposed legislation would:

A. Permit, under license by the Commission, the private ownership of power reactors, and processing facilities, the production of fissionable material incident to the operation of such reactors, and processing facilities, and the private ownership and possession of any fissionable material used or produced in connection with the operation of the reactor or processing facilities. The Atomic Energy Act presently forbids the private ownership of fissionable material or of reactors capable of producing substantial quantities of fissionable material, and prohibits the private production of fissionable material except to a limited extent in connection with research and development activities.

B. Provide, for Commission regula-

tion of the safety and security aspects of licensed activities.

C. Authorize, the Commission to make long-term commitments for the sale or lease to licensees of source, fissionable or other special materials required in the development, construction or operation of power reactors.

D. Authorize, but does not require, the Commission to purchase any fissionable or by-product materials produced by licensees in the operation of their reactors.

The following paragraphs discuss particular features of the legislation.

Antitrust Provisions

Section 7 of the present Atomic Energy Act, which deals with the licensing of commercial applications of atomic energy, contains the following provisions:

"Where activities under any license might serve to maintain or to foster the growth of monopoly, restraint of trade, unlawful competition, or other trade position inimical to the entry of new, freely competitive enterprises in the field, the Commission is authorized and directed to refuse to issue such license or to establish such conditions to prevent these results as the Commission, in consultation with the Attorney General, may determine. The Commission shall report promptly to the Attorney General any information it may have with respect to any utilization of fissionable material or atomic energy which appears to have these results."

Section 3 of the proposed legislation substitutes for this provision language very similar to that contained in the Federal Property and Administrative Services Act relating to the disposal by the Government of large surplus plants. It requires the Commission before issuing any license to obtain the views of the Attorney General as to whether the issuance of the license would tend to create or maintain a situation inconsistent with the antitrust laws. The ultimate decision with respect to issuance of the license would, however, rest with the Commission.

The advantages of this provision over the provisions of the present Act lie primarily in substituting for the broad and unusual criteria of Section 7 the criterion of consistency with the antitrust laws, which has acquired over a period of years through administrative and judicial interpretation a more definite content than the provisions of the present Atomic Energy Act.

(Continued on p. 92)

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International Control

The proposed legislation contains provisions relating to the international control of atomic energy identical to those contained in Section 8 of the Atomic Energy Act. Should an international control plan interfere with the commercial activities or property rights of licensees, the Congress will presumably wish at that time to consider legislation providing appropriate compensation to any licensees who are affected.

Licensing of Production

The proposed legislation provides that the provisions of Section 7 of the Atomic Energy Act, which relate to licensing of the commercial uses of atomic energy, shall not be applicable to any license or licensed activity under the new legislation. In effect, the proposed legislation repeals Section 7 as to such licenses and activities. The principal provisions of Section 7 which are in effect repealed are (a) the prohibition on the licensing of any activity involving the production of fissionable material, (b) the requirement of a 90-day waiting period after submission of a report to the Congress prior to the issuance of any license, and (c) the requirement that licenses be revocable at any time by the Commission. Certain of the provisions of Section 7 have, however, been incorporated in the new legislation.

Security Regulations

Section 4 of the proposed legislation provides for Commission regulation of licensed activities to prevent the loss or diversion of source or fissionable material and to control the dissemination of and access to restricted data in the possession of licensees. Provision has not been made for regulation by the Commission solely for the purpose of protecting the physical security of the reactor and associated facilities against sabotage or other source of physical injury. There appears to be no basic reason why privately owned power reactors should be placed in a different category in this respect from other privately owned production facilities which are vital to our national defense.

In addition to the provision for security regulations, all information and data developed by licensees which fall within the description of "restricted data" in Section 10(b)(1) of the present Act would be subject to the penal provisions of that section relating to unauthorized disclosure and disposition of restricted data.

Personnel Security

Provision is made for investigation and clearance of persons permitted by licensees to have access to restricted data. Investigations should be performed by the Civil Service Commission, except for FBI investigations where derogatory information concerning loyalty was developed. Emergency clearances would be limited to cases of emergencies affecting the public interest.

Consideration is now being given by the Commission to legislation which would permit the Commission to relate the scope and detail of personnel investigations to the sensitivity of the information involved. An alternative approach, also under consideration, might be the removal of certain less sensitive areas of classified information from the personnel clearance requirements altogether. Since the impact of such legislation would extend generally to the Commission's activities, these legislative suggestions have not been considered as a part of this legislative proposal.

Patents

The submitted draft of proposed legislation does not include any provisions in respect to amendment of the patent section of the Atomic Energy Act. Possible amendments to the patent section are being given separate consideration.

Atomic Industrial Forum Elects Officers

Atomic Industrial Forum, Inc., the new association of organizations working in atomic energy (NU, May '53, p. 70), has held its first board meeting and elected as president Walker L. Cisler and as vice presidents Frederick L. Hovde and Alfred Iddles.

Cisler is president of the Detroit Edison Co., Hovde is president of Purdue University, and Iddles is president of the Babcock & Wilcox Co.

The forum has three classes of membership, members, associate members, and organization members (see p. 82). The yearly dues structure for the forum has been set as follows: individuals, $25; corporations with sales under $1-million, $200; with sales be-

tween $1-million and $10-million, $500; with sales between $10-million and $100-million, $1,000; and with sales over $100-million, $2,000.

Two new members have been elected to the board. They are Francis K. McCune, general manager, atomic products division, General Electric Co., and John Perry Yates, senior vice president, Bechtel Corp.

Michigan Project to Build Research Reactor

The Michigan Memorial-Phoenix Project of the University of Michigan will build a swimming-pool type research reactor with a $1-million grant it has received from the Ford Motor Company Fund. A detailed design and a plan for operation of the reactor will be presented to the Atomic Energy Commission for approval.

The reactor will be a swimming-pool type and will have a higher power rating than the water boiler now nearing completion at North Carolina State College. Fuel for the reactor will be U^{235} in the form of plates submerged in a tank filled with 30,000 gallons of water.

A specially built structure about 50 ft square, three stories high, and with 5-ft-thick concrete walls will house the reactor. The building is planned as a wing of the Phoenix Memorial Laboratory which is scheduled to go into construction this year.

In addition to the design and operation plan that must be submitted to AEC, an analysis of the health and safety hazards and security considerations involved in the operation of the reactor must also be submitted.

Several specific projects have already been proposed for using the reactor for studies in such fields as medicine, botany, bacteriology, engineering, physics, chemistry, and architecture.

The grant brings to $7,353,000 the total subscribed to the Michigan Memorial-Phoenix Project.

Corbin Allardice Gets Joint Committee Post

Corbin Allardice has been appointed to succeed William L. Borden as executive director of the Joint Congressional Committee on Atomic Energy.

Allardice previously was director of the public information service of the New York Operations Office of the Atomic Energy Commission. Borden resigned the directorship to take a post with the atomic energy division of Westinghouse Electric Corp.

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PRESENTS 2 NEW COUNTER TUBES . . .

THE POPULAR IB85 . . . *5 TIMES STRONGER*

THE NEW 6306 . . . *A HIGH EFFICIENCY COMPANION*

Victoreen's time-tested, aluminum sheathed IB85 counter tube for detecting beta and gamma radiation has been redesigned for greater strength and durability. The aluminum shell now has five times its former over-all strength. It will also withstand three times as much point (finger) pressure. You can dent the tube shell as much as a quarter of an inch and still obtain satisfactory operation.

The IB85 tube has had wide acceptance because of high performance at lowest cost, matched uniformity from tube to tube and simple mounting structure. Now, with the new stronger shell, all of these outstanding features are combined to rank the IB85 as tops by those who know a quality product. **Price: $7.50.**

Victoreen announces the type 6306, a new companion for the IB85. Victoreen engineers have developed this Bismuth-cathode counter tube having efficiency six times greater than standard counter tubes in I_{131}, and twice as efficient on Radium. The 6306 has the same dimensions and electrical characteristics as the improved IB85.

NOTE THESE ADVANTAGES . .

SMOOTH WALL for easier cleaning . . . handling . . . immersion . . . mounting.

UNIFORMITY for interchangeability without circuit adjustments . . . parallel operation without decoupling.

LOW COST for multiple tube applications such as: cosmic research . . . aerial prospecting . . . hand and foot monitors . . . laundry, area and process monitors.

The 6306 is in the low cost range too. **Price: $15.00**

WRITE FOR FACTUAL DATA SHEETS ON THESE AS WELL AS YOUR OTHER COMPONENT REQUIREMENTS

The Victoreen Instrument Co.

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2 Heavy duty built for *high* pressure use.

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International Control

The proposed legislation contains provisions relating to the international control of atomic energy identical to those contained in Section 8 of the Atomic Energy Act. Should an international control plan interfere with the commercial activities or property rights of licensees, the Congress will presumably wish at that time to consider legislation providing appropriate compensation to any licensees who are affected.

Licensing of Production

The proposed legislation provides that the provisions of Section 7 of the Atomic Energy Act, which relate to licensing of the commercial uses of atomic energy, shall not be applicable to any license or licensed activity under the new legislation. In effect, the proposed legislation repeals Section 7 as to such licenses and activities. The principal provisions of Section 7 which are in effect repealed are (a) the prohibition on the licensing of any activity involving the production of fissionable material, (b) the requirement of a 90-day waiting period after submission of a report to the Congress prior to the issuance of any license, and (c) the requirement that licenses be revocable at any time by the Commission. Certain of the provisions of Section 7 have, however, been incorporated in the new legislation.

Security Regulations

Section 4 of the proposed legislation provides for Commission regulation of licensed activities to prevent the loss or diversion of source or fissionable material and to control the dissemination of and access to restricted data in the possession of licensees. Provision has not been made for regulation by the Commission solely for the purpose of protecting the physical security of the reactor and associated facilities against sabotage or other source of physical injury. There appears to be no basic reason why privately owned power reactors should be placed in a different category in this respect from other privately owned production facilities which are vital to our national defense.

In addition to the provision for security regulations, all information and data developed by licensees which fall within the description of "restricted data" in Section 10(b)(1) of the present Act would be subject to the penal provisions of that section relating to unauthorized disclosure and disposition of restricted data.

Personnel Security

Provision is made for investigation and clearance of persons permitted by licensees to have access to restricted data. Investigations should be performed by the Civil Service Commission, except for FBI investigations where derogatory information concerning loyalty was developed. Emergency clearances would be limited to cases of emergencies affecting the public interest.

Consideration is now being given by the Commission to legislation which would permit the Commission to relate the scope and detail of personnel investigations to the sensitivity of the information involved. An alternative approach, also under consideration, might be the removal of certain less sensitive areas of classified information from the personnel clearance requirements altogether. Since the impact of such legislation would extend generally to the Commission's activities, these legislative suggestions have not been considered as a part of this legislative proposal.

Patents

The submitted draft of proposed legislation does not include any provisions in respect to amendment of the patent section of the Atomic Energy Act. Possible amendments to the patent section are being given separate consideration.

Atomic Industrial Forum Elects Officers

Atomic Industrial Forum, Inc., the new association of organizations working in atomic energy (NU, May '53, p. 70), has held its first board meeting and elected as president Walker L. Cisler and as vice presidents Frederick L. Hovde and Alfred Iddles.

Cisler is president of the Detroit Edison Co., Hovde is president of Purdue University, and Iddles is president of the Babcock & Wilcox Co.

The forum has three classes of membership, members, associate members, and organization members (see p. 82). The yearly dues structure for the forum has been set as follows: individuals, $25; corporations with sales under $1-million, $200; with sales be-

tween $1-million and $10-million, $500; with sales between $10-million and $100-million, $1,000; and with sales over $100-million, $2,000.

Two new members have been elected to the board. They are Francis K. McCune, general manager, atomic products division, General Electric Co., and John Perry Yates, senior vice president, Bechtel Corp.

Michigan Project to Build Research Reactor

The Michigan Memorial-Phoenix Project of the University of Michigan will build a swimming-pool type research reactor with a $1-million grant it has received from the Ford Motor Company Fund. A detailed design and a plan for operation of the reactor will be presented to the Atomic Energy Commission for approval.

The reactor will be a swimming-pool type and will have a higher power rating than the water boiler now nearing completion at North Carolina State College. Fuel for the reactor will be U^{235} in the form of plates submerged in a tank filled with 30,000 gallons of water.

A specially built structure about 50 ft square, three stories high, and with 5-ft-thick concrete walls will house the reactor. The building is planned as a wing of the Phoenix Memorial Laboratory which is scheduled to go into construction this year.

In addition to the design and operation plan that must be submitted to AEC, an analysis of the health and safety hazards and security considerations involved in the operation of the reactor must also be submitted.

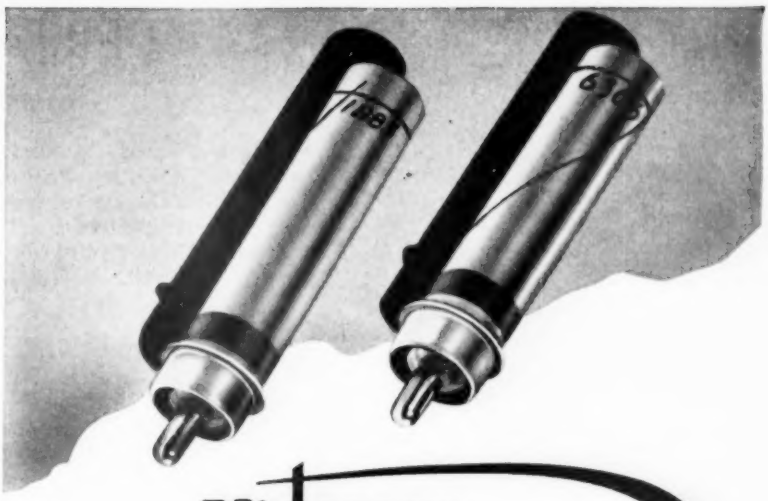
Several specific projects have already been proposed for using the reactor for studies in such fields as medicine, botany, bacteriology, engineering, physics, chemistry, and architecture.

The grant brings to $7,353,000 the total subscribed to the Michigan Memorial-Phoenix Project.

Corbin Allardice Gets Joint Committee Post

Corbin Allardice has been appointed to succeed William L. Borden as executive director of the Joint Congressional Committee on Atomic Energy.

Allardice previously was director of the public information service of the New York Operations Office of the Atomic Energy Commission. Borden resigned the directorship to take a post with the atomic energy division of Westinghouse Electric Corp.



Victoreen

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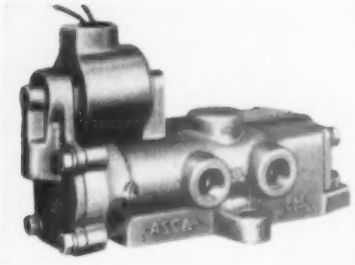
PRODUCTS AND MATERIALS

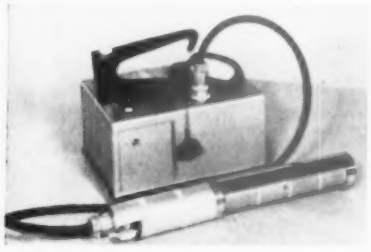


Solenoid Valve

Automatic Switch Co., Orange, N. J. This four-way packless poppet-type solenoid valve operates up to 750 cpm, intermittent duty, and up to 500 cpm, continuous duty, with air or gas as the medium; it also operates on oil or water. Four-way operation can be changed into 5-way operation by replacing the rear plate. In 4-port (common pressure) operation, an optional adjustable flow-regulating device permits control of the supply of air, gas or liquid to cylinder no. 2. With 5-port operation, two operating pressures can be introduced. (P-1)

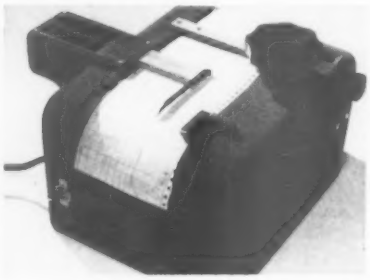
Tagged Compounds

Tracerlab, 130 High St., Boston 10, Mass. Carbon-14 labeled *dl*-epinephrine-*d*-bitartrate (cat. no. L7-8) is available with a specific activity of 1 mc/millimole. Alloxan-2-C^{14} (cat. no. L7-7) is available with a specific activity of 0.5 mc/millimole; minimum ordering quantity is 0.1 mc. (P-2)



Survey Meter

Radioactive Products, Inc., 443 W. Congress St., Detroit 26, Mich. The model D-5 survey meter, when used with the models D-5A and D-5B probes, covers radiation ranges from low-level alpha contamination to 625 mr/hr gamma radiation. The instrument monitors flat and irregular surfaces, or holes and corners. Included are a metal plug-in battery box, a roll-over bottom stainless-steel screen to minimize contamination traps, and a flashing light to indicate when the instrument is in operation. (P-3)



Square Root Planimeter

Librascope, Inc., 1607 Flower St., Glendale 1, Calif. This square root planimeter is designed for flow-chart totalizing of 3-in. miniature graphic panel strip-chart recorders. It provides for true square root extraction and integration without approximation over the entire range of flow. Totalizing is accommodated from leading to trailing edge of chart paper by means of a motor-driven sprocket. Readout is to four places. (P-4)

Mercury Recovery Unit

Acme Protection Equipment Co., 3037 W. Lake St., Chicago 12, Ill. The Mer-Vac is a combination gas-mask canister for mercury vapor collection and vacuum cleaner for mercury recovery. The unit includes a synchronous timer indicating when canister contents must be replaced; an air-circulation system for the motor, preventing amalgamation of wiring connections and parts; glass trap for mercury recovery; stainless steel and porcelain enameled canister parts; and an acid-resistant dust filter. (P-5)

Sample Spinner

Nuclear Instrument & Chemical Corp., 229 W. Erie St., Chicago 7, Ill. The model PM-1 sample spinner has a constant-speed turntable which rotates sample pans up to 2 in. in diameter at 20 rpm. The model PM-2 air-dryer and model PM-3 infrared lamp attachments are auxiliary drying units. Provision is made for connecting a compressed air supply to direct air or gas across the sample. (P-6)

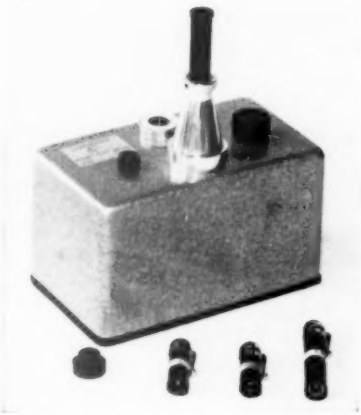
Valve Combinations

The Special Screw Products Co., 5445 Dunham Rd., Bedford, Ohio. Powell valves, in stainless or Monel, are available with machined-in flared-tube connections for tubing through 1 in. o. d. Line leaks are guarded against by Teflon-reinforced double-sealing seats. Valves furnished include needle, globe, gate and check. (P-7)

Sealed, Self-Shielded Relay

Weston Electrical Instrument Corp., 591 Frelinghuysen Ave., Newark 5, N. J. The model 723 magnetic-con-

tact-type relay is sealed against moisture and has a self-shielded core magnet mechanism and built-in solenoid release device. Double or single magnetic contacts, for contact on either increasing or decreasing values, have contact capacity of 100 ma at 120 volts, a-c or d-c. Sensitivities are available up to 2-0-2 μa; a-c and d-c ranges can be supplied self-contained up to 500 volts. Accuracy is $\pm 5\%$ for d-c and $\sim 10\%$ for a-c. (P-8)



Roentgen Meters

Landsverk Electrometer Co., 500 W. Garfield Ave., Glendale 4, Calif. This set of three roentgen meters, including models L-101, L-102 and L-103, provides ranges of 500 mr, 5 r and 50 r. The meters are sealed against dirt and moisture and are claimed to withstand rough handling without failure. Energy dependence is slight; a correction curve is provided. The meters can be exposed directly in hard X-ray and gamma-ray beams without shielding the insulation. Meters and the model L-61 charger-reader come with carrying case. (P-9)

X-Ray Image Amplifier

North American Philips Co., Inc., 750 S. Fulton Ave., Mount Vernon, N. Y. The X-ray image amplifier is said to produce images 800 to 1,200 times brighter than those obtained with the conventional fluoroscope. Operation is by means of a hemispherical fluorescent screen, an electrostatic elec-

RADIATION SURVEY METERS

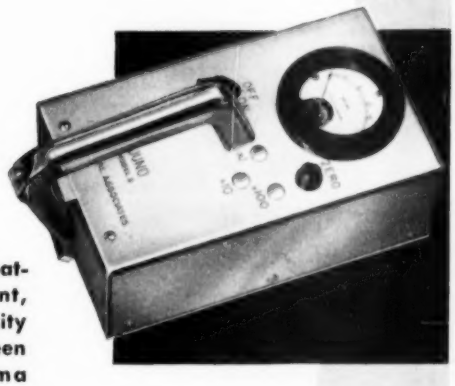
New CUTIE PIE

A self-contained battery-operated air ionization chamber instrument for use in probing for beta and gamma radiation. Provided with shield for rejecting beta particles.

- **EASY TO DECONTAMINATE.** Highly polished formed aluminum case and especially cast low-porosity handle.
- **MOISTURE-PROOF.** 1-piece gasketed case.
- **SIMPLE TO OPERATE.** Only 2 controls. Easily read 3" meter.
- **3 SENSITIVITY RANGES.** 50, 500, and 5000 MR/HR.
- **IMPROVED BATTERY PACK.** Only half as many batteries as in previous models, resulting in trouble-free operation.

Improved JUNO

Models SRJ-3 and HRJ-3



A portable, lightweight, battery-operated instrument, which measures the intensity of, and distinguishes between alpha, beta, and gamma radiation.

- **REDESIGNED CASE.** Better design has eliminated many joints and pockets, providing easy decontamination. Major joints are gasketed to minimize moisture effects.
- **STRONG ALUMINUM HANDLE.** Durable handle is especially cast and highly polished for minimum porosity.
- **FEWER BATTERIES.** Improved battery pack requires less batteries and provides more reliable operation.
- **3 RANGES IN EACH MODEL: SRJ-3 (standard range): 50, 500, and 5000 MR/HR. HRJ-3 (high range): 250, 2500, and 25000 MR/HR.**

Both instruments were developed for the Hanford Works

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3) Low cost.

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Hi-D*

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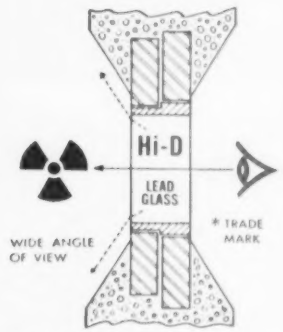
IN STEEL WALLS



Hi-D Lead Glass Windows in concrete walls are dry, and hence are completely dependable. Where the viewing problem is mainly wide-angle vision, Hi-D Glass is fully competitive in price with zinc bromide.

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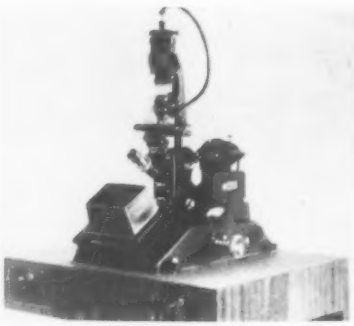
tronic lens and an optical microscope. Equipment includes a lead-lined aluminum jacket for the tube and a 25-kv d-c power supply. (P-10)



Universal Microscope

Opplem Co., Inc., 352 Fourth Ave., New York 10, N. Y. With the ZC Galileo universal microscope, magnifications from 4× to 3,000× can be run with continuity on the ground-glass screen of the camera. Magnification of any objective set-up can be instantly increased or decreased 4 times without recentering. Macro-photography can be done down to 5× without disturbing specimens. Eyepiece viewing and photographing on both still and movie camera can all be done at the same time. Transmitted light permits simultaneous projection up to 20 ft on a 40-in. screen. (P-11)

Analog-Digital Converter

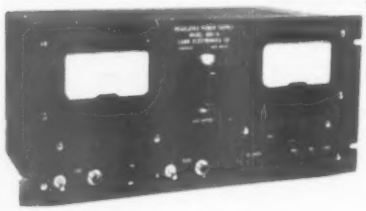
Consolidated Engineering Corp., 300 N. Sierra Madre Villa, Pasadena 8, Calif. The model 34-104 analog-to-digital converter, together with the CEC analytical mass spectrometer, records the digital values of peak heights for up to 40 preselected mass numbers. Peaks may be in the mass ranges of 40–150 or 12–122; 10 sec are required to record each peak height. Values are displayed by decimal-coded lights as well as recorded by punchcard or typed readout. Digital conversion is accurate to 0.1% full-scale. (P-12)

Temperature-Control Bath

Service Metal Fabricators Co., 350 N. Foothill Rd., Beverly Hills, Calif. The temperature control bath provides operating temperatures from 32° to 100° F $\pm\frac{1}{4}$° F. Refrigeration and heating circuits are actuated by mercoid switches operating from thermocouples in the tank. The water is circulated over cooling coils and heating unit and through a filtering system by a centrifugal pump. The stainless-steel tank is 27 in. long, 17 in. wide and 15 in. deep. (P-13)

Organic Extraction Apparatus

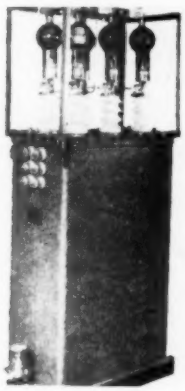
Scientific Glass Apparatus Co., Inc., Bloomfield, N. J. The Schmall apparatus is designed for extraction and determination of salts of organic bases and acids. Extraction is automatic and washings are eliminated. In conjunction with titrations in nonaqueous solvents, transfers are eliminated and sharper end points obtained. Results are claimed to show good agreement with those obtained by the U. S. Pharmacopeia or conventional procedures. Two types of liquid-liquid extractors are available, one for solvents lighter than water, the other for those heavier than water. (P-14)



Regulated Power Supply

Lawn Electronics Co., E. Freehold Rd., Freehold, N. J. The model 630-A regulated d-c power supply provides 0.1% regulation, <1 mv ripple and <½-ohm output impedance. Output is continuously variable from 0 to 600

volts with positive or negative terminal grounded; the unit supplies up to 300 ma at any voltage setting. Bias supply is variable from zero to −250 volts stabilized to 0.1 volt; center-tapped filament supply provides 6.3 volts, 6 amperes. (P-15)



Rectifier-D-C Source

Magnatran, Inc., Kearny, N. J. The "Unitized Rectifier" incorporates a high-voltage d-c source. Immersion of components in askarel or oil provides cooling and insulation. Tube life is claimed to be prolonged by out-of-phase filament operation. Output voltages are available to 50 kv, d-c. Filter chokes are obtainable in suitable ranges. (P-16)

Plug-In Meters

Cole Instrument Co., 1320 S. Grand Ave., Los Angeles 15, Calif. These plug-in electrical meters are available in standard and special calibrations in 3 or 4 in. sizes. The meters are interchangeable and are pulled out and replaced by hand. (P-17)

High-Impedance Delay Cable

Columbia Technical Corp., 5 E. 57th St., New York 22, N. Y. The type HH-2000 delay cable, 0.405 in. o. d., has a time delay of 0.11 μsec ft and nominal characteristic impedance of

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the ALL-TEFLON
and STAINLESS STEEL
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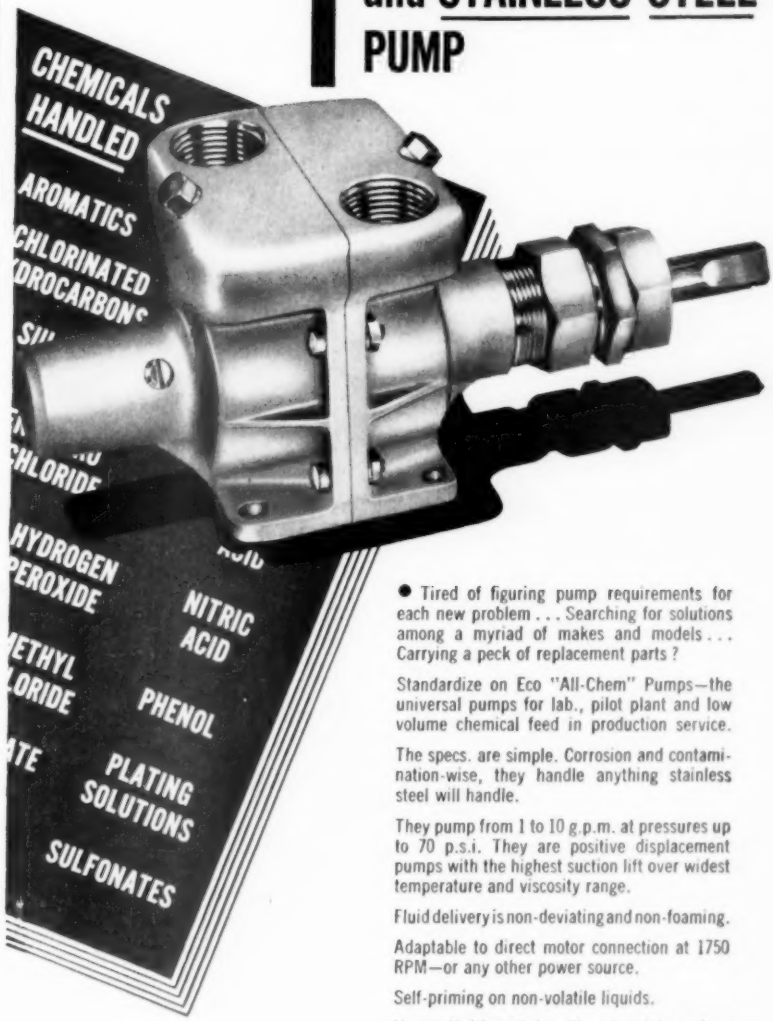

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Fluid delivery is non-deviating and non-foaming.

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Self-priming on non-volatile liquids.

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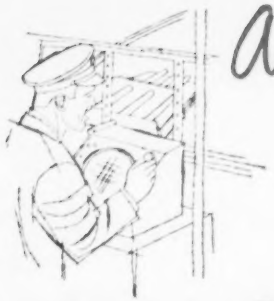

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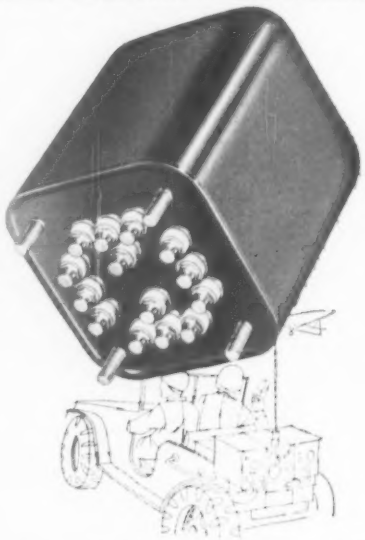
The complete MS (Military Standard) line of Hermetically-Sealed Power & Filament Transformers

CHICAGO TRANSFORMER now offers all units in the Military Standard (MS) line, as established jointly by the three armed forces (Army Signal Corps, Navy Bureau of Ships, and Air Force) working through ASESA (Armed Services Electronic Standards Agency) and in cooperation with the transformer industry. The complete line is housed in CHICAGO's one-piece drawn-steel cases. Outside case dimensions and mounting dimensions are within the tolerances of the Military Standard specification. Terminal arrangements and markings are also in accordance with the same specification. Tests conducted in the CHICAGO TRANSFORMER laboratories indicate that all units will meet the requirements of Grade 1, MIL-T-27 specifications for Class A operation. The Military Standard line should find wide usage in military airborne, marine, and ground communication equipment, and particularly for research and development applications, pilot runs and pre-production models.



POWER TRANSFORMERS—INPUT REACTOR SYSTEMS (PRIMARY—105/115/125 V.—Frequency 54-66 cycles)

CATALOG NUMBER	MIL-T-27 PART NO.	HIGH VOLTAGE SECONDARY A-C Volts	D-C MA.	D-C V OUTPUT	RECT. FIL. Volts	Amps.	FIL. NO. 2 Volts	Amps.	WT. LBS.
PMS-70	MS-90026	200-100-0-100-200	70	385	6.3 5	2	6.3	3	4
PMS-70A	MS-90027	325-0-325	70	260	6.3 5	2	6.3	4	5
PMS-150	MS-90028	325-0-325	150	245	6.3	5	5	3	7¼
PMS-175	MS-90029	400-0-400	175	318	5	3	6.3	8	10
PMS-250	MS-90030	450-0-450	250	345	5	3	6.3	8	13
PMS-350	MS-90031	350-0-350	250	255					7½
PMS-550	MS-90032	550-0-550	250	419					11
PMS-800	MS-90036	800-0-800	250	640					16½

FILAMENT TRANSFORMERS (PRIMARY:—105/115/125 V.—Frequency 54-66 cycles)

CATALOG NUMBER	MIL-T-27 PART NO.	SECONDARY Volts	Amps	INSULATION VOLTS RMS	WT. LBS.
FMS-23	MS-90016	2.5	3.0	2500	1½
FMS-210	MS-90017	2.5	10	2500	2½
FMS-53	MS-90018	5.0	3.0	2500	1¾
FMS-510	MS-90019	5.0	10	2500	4
FMS-62	MS-90020	6.3	2.0	2500	1¾
FMS-65	MS-90021	6.3	5.0	2500	2¾
FMS-610	MS-90022	6.3 CT	10	2500	5
FMS-620	MS-90023	6.3	20	2500	8
FMS-210H	MS-90024	2.5	10	10000	4¾
FMS-510H	MS-90025	5.0	10	10000	7

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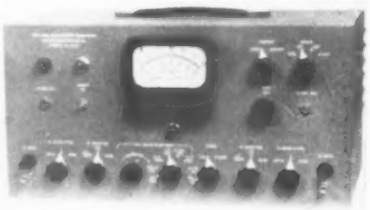
2,200 ohms. Attenuation for 1-μsec delay is practically zero up to 3 Mc, 0.5 db at 5 Mc and 2.5 db at 10 Mc. Bandwidth for 1-μsec delay is 0–10 Mc. Maximum operating voltage is 2,000 volts, rms. (P-18)

Oil Diffusion Pump

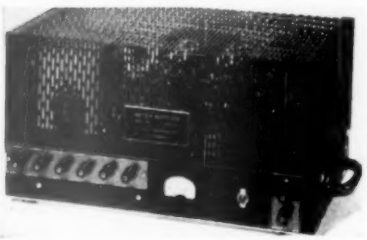
Central Scientific Co., 1700 Irving Park Rd., Chicago 13, Ill. The OD-25 oil diffusion pump is said to be easy to take apart for cleaning and quickly connected or disconnected. The pump is based on the principle of entrapping gas or air molecules by a stream of oil vapor, the oil being vaporized by the application of heat. All parts are of cold-rolled steel except the brass couplings and the copper cooling coil. Exterior finish is copper and nickel plated and the inside is copper plated to prevent rusting. Couplings are white nickel plated. (P-19)



Phase Meter

Advance Electronics Co., Box 394, Passaic, N. J. The type 404A phase meter gives direct indication of phase angle between two alternating voltages of any waveform, symmetrical or unsymmetrical, from 100 kc down to +0 cps, with an external indicator, and 100 kc to 0.001 cps with panel meter. The phase range is 36, 90, 180 and 360 deg full scale, lead or lag. Input is 0.5–300 volts from +0 to 10 kc; the lower limit increases to 1 volt at 100

ke. Accuracy is ±1% to 10 kc and increases to 4% at 100 kc with external indicator; panel meter introduces additional error of 1.5%. (P-20)



Power Frequency Amplifier

Keithley Instruments, 3868 Carnegie Ave., Cleveland 15, Ohio. The model 105 power frequency amplifier tests the secondary voltage of synchros and other circuits requiring meter-current corrections. Input impedance of the amplifier requires less than 150 μa from the test circuit; it provides 0.05–0.07 ampere to the measuring voltmeter or wattmeter. Connections for 15, 75, 150, 300 and 600 volt inputs are provided, with 150-volt output in each case. Instrument is said to add <0.15% error to measurements. (P-21)

Potentiometer Kit

Servotrol Co., Framingham Centre, Mass. Pot Kit B, designed for experimental breadboarding and calculating, contains "unitized" type RVC2 potentiometers, mounting plates, clamp rings, servocalculator and brochure. Included are one 360-deg sine potentiometer and 14 linear potentiometers with equally spaced taps. (P-22)

Wide-Range Oscillator

Hewlett-Packard Co., 395 Page Mill Rd., Palo Alto, Calif. The model 200CD oscillator has a range of 5 cps

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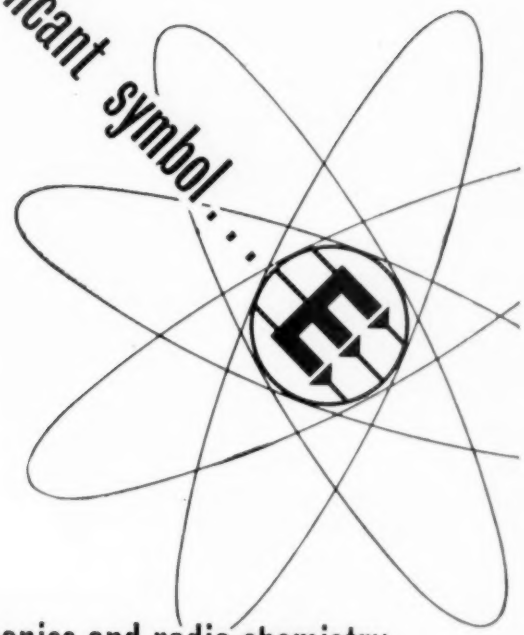

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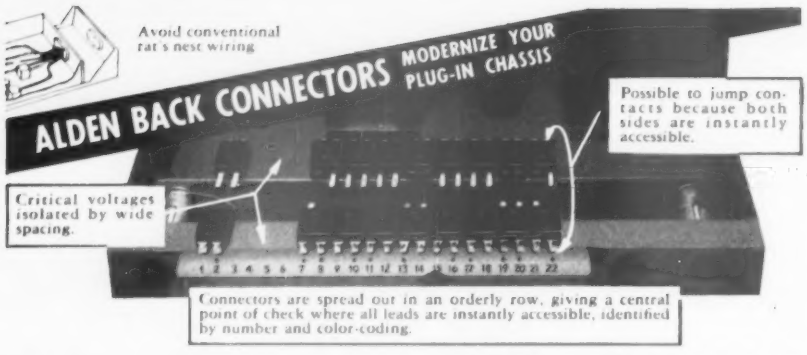
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Connectors are spread out in an orderly row, giving a central point of check where all leads are instantly accessible, identified by number and color-coding.

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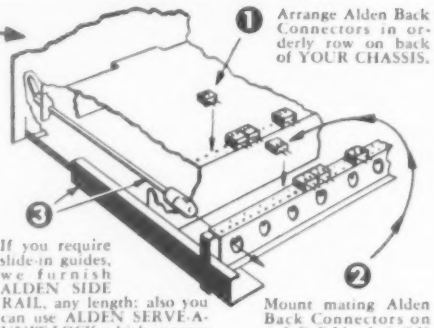
1
Arrange Alden Back Connectors in orderly row on back of YOUR CHASSIS.
2
Mount mating Alden Back Connectors on ALDEN LOCK FRAME. It's prepunched and tapped to screw in the Back Connectors.
3

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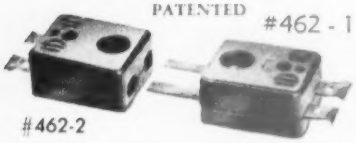

#462-2

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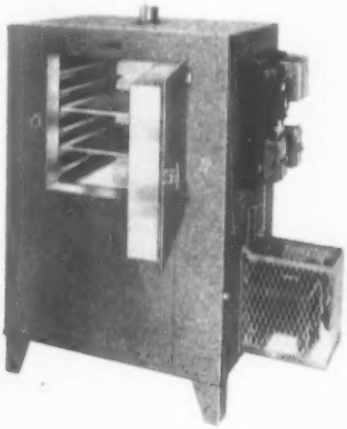
to 600 kc, ±2% in five overlapping decade bands. It provides a maximum of 10 volts across its rated load of 600 ohms, and 20 volts open circuit. Distortion is less than 1% over the entire frequency range, independent of load impedance. (P-23)

Quartz Crystals

James Knights Co., Sandwich, Ill. Gold- or silver-plated quartz crystals, hermetically sealed in 6V6GT glass envelopes, are available as models G-9J and G-9; they are wire mounted with an octal base. The G-9J has a range of 1.2–10 kilocycles, with a frequency tolerance of ±0.03% at −40° to +70° C, and a capacity ratio of 200. Model G-9 has a range of 5–200 kc, with a frequency tolerance of ±0.02% at −40° to +70° C, and capacity ratio from 1,000 to 200. (P-24)



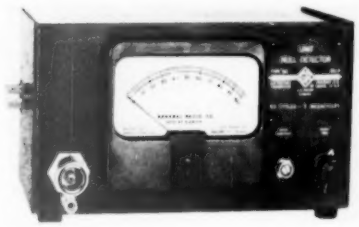
Cabinet Ovens

Grieve-Hendry Co., Inc., 1811-19 W. Lake St., Chicago 12, Ill. These ovens are equipped with a high-pressure motor-driven blower which propels heated air in a definite air-flow pattern. The ovens have indicating temperature control, adjustable air flow, manual interlock for blower operation without heat, and adjustable positive exhaust and intake. They are available in either horizontal or vertical flow and temperatures to 650° and 850° F. (P-25)

Chemically-Inert Filter

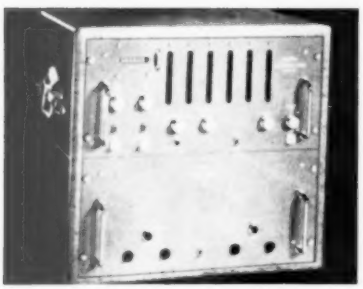
Porous Plastic Filter Co., 30 Sea Cliff Ave., Glen Cove, N. Y. These porous Kel-F (polychlorotrifluoroethylene manufactured by M. W. Kellogg Co.)

filters are claimed to be inert to all strong acids, caustics, oxidizing agents and common organic solvents. They are useable up to 300° F, have ultimate tensile strength of 900 psi and modulus of elasticity of 1,800 psi; mean pore opening is 15 microns. Flow capacities range downward from 500 ft³/min per ft² of filter surface, at 8 psi differential pressure, and from 110 gal/min of water per ft² at 10 psi differential pressure. Disks are available with up to 12-in. diameter and $\frac{1}{16}$-in. and $\frac{1}{8}$-in. thicknesses. (P-26)



Unit Null Detector

General Radio Co., 275 Massachusetts Ave., Cambridge 39, Mass. The type 1212-A unit null detector is designed primarily as a balance indicator for a-c bridges. Frequency characteristic is flat within about 1 db from 50 cycles to 500 kc; it is claimed to be satisfactory as an indicator from 20 cycles to 5 Mc. Logarithmic relationship between meter reading and input voltage gives full-scale deflection of 100 volts and deflection of 1% of full scale for $< 40\ \mu v$. (P-27)



Time-Interval Meter

Beckman Instruments, Inc., Berkeley Scientific Div., 2200 Wright Ave., Richmond, Calif. The model 5120 time-interval meter provides direct reading of elapsed time between two events, in 1-μsec increments, to a maximum of 1 sec with an accuracy of ± 1 μsec, $\pm$ crystal drift. Attenuators permit selection of amplitude of start and stop voltages at optimum level for elimination of interference. Display

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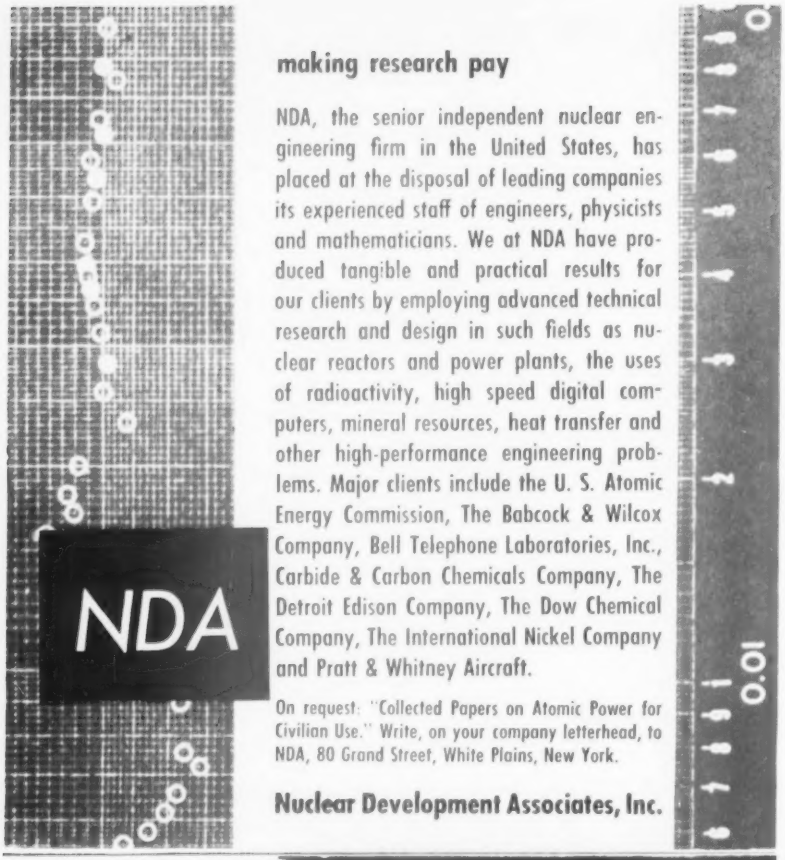
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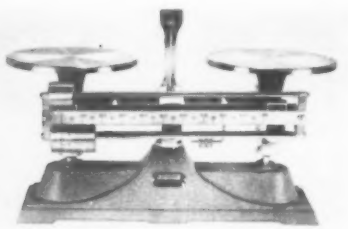
time can be controlled manually or automatically up to 5 sec. Power is available from an accessory socket to operate various transducers. (P-28)

Elapsed-Time Indicator

Marion Electrical Instrument Co., Manchester, N. H. The HM2ET elapsed time indicator is hermetically sealed and operates from −55° to 85° C. It is available in $^1/_{10}$-hr steps to 9,999.9, or hour steps to 99,999. Self-starting synchronous motor is either 110–125 or 220–250 volt for 50 or 60 cycle a-c operation. Drawn-steel case provides magnetic shielding. (P-29)

Vacuum-Tight Tube Fittings

Crawford Fitting Co., 884 E. 140th St., Cleveland 10, Ohio. Swagelok tube fittings provide vacuum-tight mechanical seals without the use of solder, mercury or vacuum grease. With an oil diffusion pump, fittings have been subjected to 10^{-8} mm mercury. Only a wrench is required for installation. No torque is exerted on tubing to which fittings are attached. Fittings are available in brass, aluminum, steel, stainless steel and monel. (P-30)



Micrometer-Poise Balance

Ohaus Scale Corp., 1050 Commerce Ave., Union, N. J. The poise of this balance provides a range of 0.5–5,000 gm without additional weights. The poise is slid along the beam for rapid traverse and rotated for final position-

ing. The poise barrel is calibrated in 0.5-gm increments. Capacity is 5,000 gm with 0.5-gm sensitivity; an undivided tare beam has 1-lb capacity. The balance is provided with 7-in. stainless steel plates, 9-in. nickel-plated brass pans, or a brass scoop. (P-31)

Cloud and Pour Test Cabinets

Precision Scientific Co., 3737 W. Cortland St., Chicago 47, Ill. Two cabinets cover the full range of cloud and pour tests. The 3-compartment cabinet operates at +30° F, 0° F and −30° F; the 2-compartment cabinet operates at −60° F and −90° F. Compartment thermostats are preset and automatically hold temperatures within 2° F. Coldest compartment reaches −90° F in 2½ hr. (P-32)

Control Valve

The Annin Co., 3500 Union Pacific Ave., Los Angeles 23, Calif. This control valve combines models 1520 SMW and 1560 SMW automatic and manual controls. The supplementary handwheel control allows shut-down operation, adjustment for maximum efficiency, and a limit stop for the automatic control. Positioning accuracy of automatic control is up to 1/1,000 of valve travel. Standard operating pressure is up to 5,000 psi, with special applications to 50,000 psi; effective temperature is −100° to 450° F. (P-33)

Gamma-Ray Source Containers

Solus-Schall Ltd., 18 22 New Cavendish St., London W1, England. The bronze shell of one of these two isotope containers for gamma radiography is filled with lead and the other with a

SQUARE PULSE GENERATORS
for the
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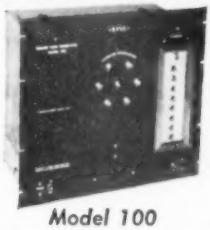

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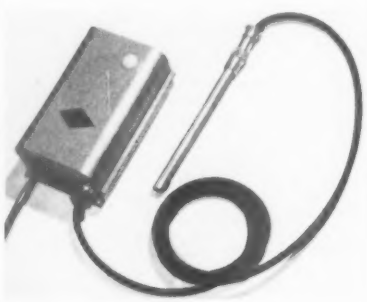
Mobile Oscillograph Table

Allen B. Du Mont Laboratories, Inc., Instrument Div., 1500 Main Ave., Clifton, N. J. The top of the type 2602 table, for mounting cathode-ray oscillographs, can be tilted from the horizontal up to 20 deg. An adjustable bar allows the oscillograph to be placed at varying depths on the tilted top. Dimensions are: 19 in. wide, 31 in. deep and 36⅝ in. high. (P-35)



Liquid-Level Control

Thermo Instruments Co., 1166 El Camino Real, Belmont, Calif. This electronic liquid-level control is based on the capacitive action of liquid surrounding a porcelain-enamel-covered electrode. Control unit and probe are

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- **OUTPUT #2:** 6.3 Volts AC CT at 5A unregulated
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- **RIPPLE OUTPUT:** Less than 10 millivolts rms

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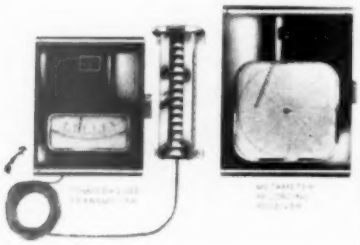
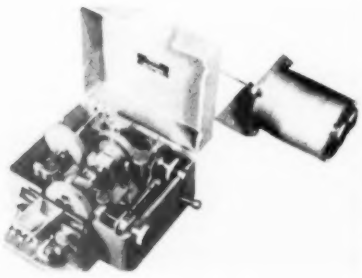
connected by cable that can be 1,000 ft long. Two main controls for liquid level and differential have screwdriver adjustment; vernier control is also provided for liquid level. Differential range varies with type of service, e.g., for ammonia control the standard unit operates between 1 and 5 in. (P-36)



Remote Temperature Recorder

The Bristol Co., Waterbury 20, Conn. The Metameter Telemeter consists of a temperature transmitter and recorder. Instruments are available in ranges from −60 to 3,600° F. With telephone wire transmission, transmitter and recorder can be many miles apart. These systems can be supplied with the kind of temperature-sensitive bulb and tubing desired. (P-37)



Microtome

Process & Instruments, 60 Greenpoint Ave., Brooklyn 22, N. Y. The motor-driven model 3 microtome cuts sections from 0.1 to 10 microns within ±0.01 micron. A rotary specimen vice head is said to avoid section pick-up. A trough filled with an alcohol-water mixture floats the section. Change of section thickness is obtained by changing the angle of inclination of a revolving inclined plane. (P-38)

Analog-to-Digital Converter

G. M. Giannini & Co., Inc., 117 E. Colorado St., Box N, Pasadena 1, Calif. This converter indicates instantaneously angular shaft positions

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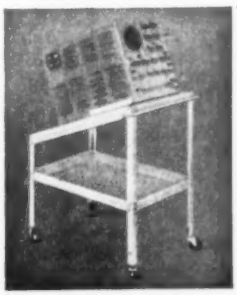

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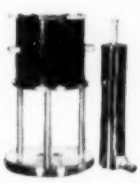

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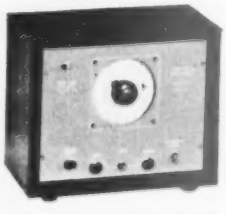

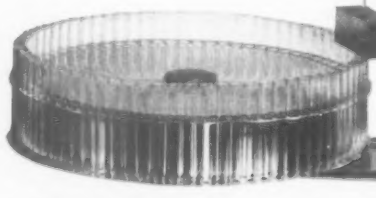

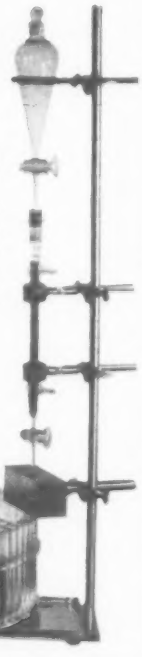

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of 360 deg or less with 0.1% accuracy without the use of gearing. Maximum shaft speed is 100 rpm. The converter can be connected directly to electromechanical printers or card-punch equipment to provide decimal digital data. (P-39)

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Superior Tube Co., Norristown, Pa. This seamless light-wall tubing is available up to $2\frac{1}{16}$ in. o. d. with wall thicknesses of 0.006–0.035 in. Tubing is furnished in 3 stainless analyses, AISI types 304, 321 and 347, and in Monel metal, with pickled or standard bright finish. It is produced in 3 tempers: fully annealed, half-hard drawn and full-hard drawn. Length range is 5–22 ft in random, multiple or cut lengths. (P-40)

INDUSTRY NOTES

▶**The Atomic Center for Instruments & Equipment, Inc., 489 Fifth Ave., New York 17, N. Y.,** now administers the R-C Scientific Instrument Co. Dosifilm badge service in the East.

▶**Radioactive Products, Inc., 443 W. Congress, Detroit 26, Mich.,** offers encapsulation services on radioactive sources. Capsules and carrying containers can be supplied either by the manufacturer or by the customer.

▶**Beckman Instruments, Inc., South Pasadena, Calif.,** has transferred its New York offices to a new 20,000 square foot plant in Mountainside, N. J. The building houses a sales and service headquarters and a branch manufacturing facility for the Helipot division.

▶**The Victoreen Instrument Co., 5806 Hough Ave., Cleveland 3, Ohio,** has appointed William W. Managan as chief engineer of the instrument division. With Victoreen since 1947, Managan has served as a senior physicist specializing in G-M tube and ionization chamber development.

▶**Automatic Switch Co., 391 Lakeside Ave., Orange, N. J.,** is opening a factory branch at 923 E. Third St., Los Angeles 13, Calif. The branch will stock equipment and function as the West Coast service center.

LITERATURE AVAILABLE

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steel shelving and lockers. *Precision Equipment Co., 3712 N. Milwaukee Ave., Chicago 41, Ill.* (L-1)

Radiation instruments. Catalog lists line of radiation detection and counting instruments. *Nuclear Measurements Corp., 2460 N. Arlington Ave., Indianapolis 18, Ind.* (L-2)

Glass apparatus. Catalog 22 describes glass apparatus, scintillation crystals and liquids, chemicals and thin films. *Wakefield Industries, Inc., Dept. FP-3, 5108 W. Grove St., Skokie, Ill.* (L-3)

Radiation equipment. Catalog M includes detection and measuring equipment. *Nuclear-Chicago, 229 W. Erie St., Chicago, Ill.* (L-4)

Dosimeter charger. Bulletin describes model 103A charger. *Arnold O. Beckman, Inc., 1020 Mission St., South Pasadena, Calif.* (L-5)

Signal converter. Bulletin P1254 describes low-power inverter. *The Bristol Co., Waterbury 20, Conn.* (L-6)

Gas analyzer. Bulletin describes continuous-stream gas analyzer. *Liston-Becker Instrument Co., Inc., 649 Hope St., Stamford, Conn.* (L-7)

Turbidity instruments. Bulletin 531 describes indicators and recorders. *Ess Instrument Co., 96 S. Washington Ave., Bergenfield, N. J.* (L-8)

Radiation detection equipment. Bulletin gives data on radiation counters, amplifiers, scalers and safety devices. *Radiation Counter Laboratories, Inc., 5122 W. Grove St., Skokie, Ill.* (L-9)

Demineralizer. MA-model sheet describes single-unit water demineralizer. *Penfield Mfg. Co., Inc., 19 High School Ave., Meriden, Conn.* (L-10)

Electronic components. Catalog contains specifications and applications for supplies, subminiature tubes, regulators and resistors. *Victoreen Instrument Co., Components Div., 3800 Perkins Ave., Cleveland 14, Ohio.* (L-11)

Mass spectrometer. General catalog describes analytical, isotope-ratio, and dual-purpose mass spectrometers. *Consolidated Engineering Corp., 300 North Sierra Madre Villa, Pasadena 15, Calif.* (L-12)

Temperature controls. Catalog G-18 describes electric, pneumatic and valve-type controls. *Burling Instrument Co., 5 Vose Ave., S. Orange, N. J.* (L-13)

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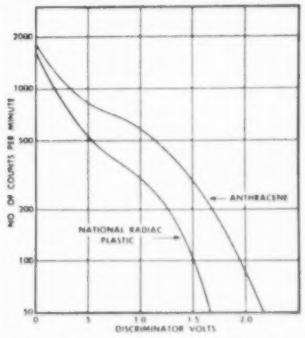

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RIDL MODEL 512 SCALER

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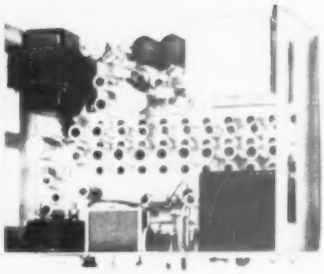

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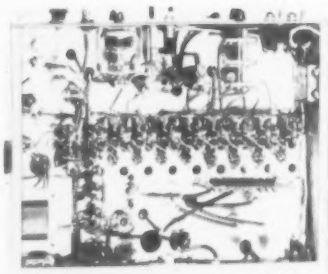

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This is the ONLY SCALER YOU NEED regardless of the type of counter you wish to use.

This unit has been successfully used with all types of counters including Geiger, proportional, scintillation, and Bernstein-Ballentine gas and solid phase counters.

- Self contained linear amplifier.
- 500 to 5000 volt continuously variable high voltage supply.
- Higginbotham scale of 512.

For complete information write for descriptive literature.

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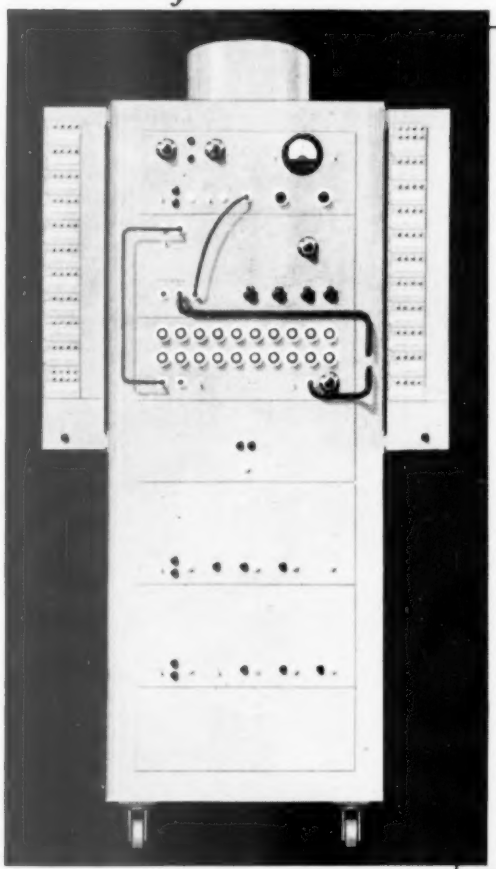
For PRECISION ANALYSIS
of Nuclear Particle Energy Spectra



Atomic's Multiple Channel Differential Pulse Height Analyzer

The Model 520 Differential Pulse Height Analyzer provides twenty channels for the simultaneous taking and recording of accurate data on the amplitude distribution of electrical signals. It can be used to divide a spectrum of 60 volts at the input of the Pulse Sorter into 120 channels, scanning 20 at a time.

This instrument enables the nuclear physicist to take spectrum data on long lived isotopes in less time, and data on short lived isotopes with fewer decay corrections than would be required using a single channel analyzer.

Although it is designed primarily to analyze the pulse height spectrum provided by nuclear particle detectors, it can be useful in the study of other phenomena where events can be expressed in terms of electrical pulses of random amplitudes and random time distribution. The Model 520 may readily be adapted to gathering data on radar receiver signal studies. It can also be used to study the statistical distribution of the response of detecting devices used in other studies.

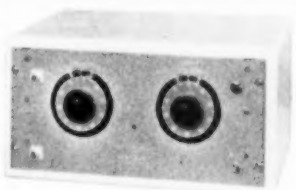
Channels — Twenty fixed adjacent channels, each 0.5 volt wide, covering a spectrum of 10 volts at the Pulse Sorter input. All channels move as a group by setting the level of the bottom of the lowest channel at any value from 0 to 50 volts.

Each channel output is fed to a scale of 16 which in turn feeds a 6-digit register, providing a visual indicaton of the number of pulses whose peaks lie within each channel. In addition to the 20 channels there are two other channels, "Total Count" and "Surplus Count". All 22 scalers and registers reset electrically from a single pushbutton.

The Model 520 includes a precision pulse generator for calibration.

Atomic's Single Channel Differential Pulse Height Analyzer.

The Model 510 Analyzer is designed for studies of the amplitude distribution of electrical pulses whose amplitudes fall in the range from zero to one hundred volts. Combined with a suitable detecting device, a linear amplifier, and a scaler, the Model 510 provides extreme flexibility for the study of the energy distribution of nuclear particles.



The lower voltage level is settable, by helical potentiometer, from zero to 100 volts; channel width or "window" is settable (as volts above baseline) from zero to 7 volts. It accepts input pulses up to approximately 1000 per second. The output pulse voltage level of the analyzer is variable from zero to −20 volts.

Linear Amplifiers . . . . for use with Model 510 Analyzer or for use with ionization chambers, scintillation, and proportional counters. Model 204B — rise time to 0.2 microseconds, gain to 15,000. Three-position band width switch. Dual attenuator, precision calibrated pulse amplitude discriminator. Low and high level outputs, self-contained power supply, provision for preamplifier. Model 204C — similar to 204B, with separate input time constant and rise time controls.

For full details on instruments described above, request Bulletin 520-I

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Roto-Matic Sample Changer

for RADIOLABORATORY SAMPLE COUNTING

Unusually versatile in use, **nuclear's** "Roto-Matic" Model C-110 Automatic Sample Changer is designed with simple mechanical operation for reliability and long operating life. This compact changer (14" x 15") uses minimum bench space, yet carries up to 50 samples at one time. Any number up to 50 can be counted, the cycle repeated, or background count recorded. There is no time lost with blank positions. All samples are counted while fully shielded by 2" of lead.

Model C-110 operates with any scaler because it incorporates eight preset count settings. It may also be controlled by a preset time or preset count scaler, or will provide preset time operation with any scaler and a suitable timer. The associated printer provides a permanent record.

Heart of the "Roto-Matic" sample changer is the simple three-position "Auto-load" turntable which selects a sample, places it in counting position within the shield, and loads it into the storage sample magazine when the count is completed. Both sample magazines are clear plastic so that progress can be easily observed. Expendable sample carriers and the chrome-plated turntable make decontamination easy if necessary.

Model C-110 Automatic Sample Changer is available on good delivery. Write for details today.

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